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NATIONAL DEFENSE INDUSTRIAL ASSOCIATION

STRENGTH THROUGH INDUSTRY & TECHNOLOGY

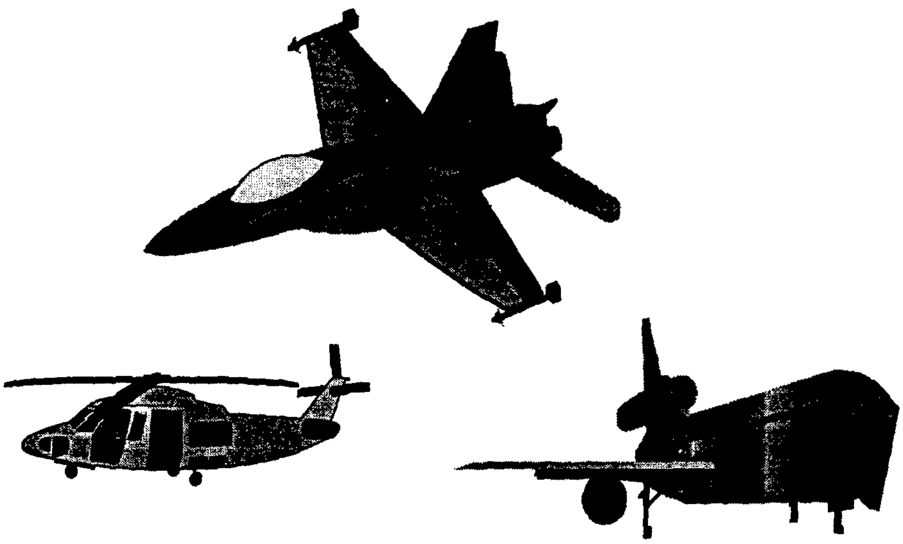
presents

Enhancing Aircraft Survivability — A Vulnerability Perspective

October 21 - 23 1997

Naval Postgraduate School

Monterey, CA



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ENHANCING AIRCRAFT SURVIVABILITY--A VULNERABILITY PERSPECTIVE
VOLUME I UNCLASSIFIED UNLIMITED

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TABLE OF CONTENTS

ENHANCING AIRCRAFT SURVIVABILITY 1
Rear Admiral Robert H. Gormley, USN, (Ret)
Chairman, NDIA Combat Survivability Division
President, The Oceanus Company

PEOPLES ISSUES 12
The Honorable John J. Goglia
Member, National Transportation Safety Board
Washington, DC

ADPA/NSIA AIRCRAFT SURVIVABILITY SYMPOSIUM - VULNERABILITY REDUCTION: CRITICAL FOR TODAY AND TOMORROW 17
Vice Admiral William C. Bowes, USN, (Ret)
Senior Vice President, Hughes Aircraft Company
Former Principal Deputy Assistant Secretary of the Navy (RD&A)
Commander, Naval Air Systems Command and
Chairman, Joint Aeronautical Commanders Group
El Segundo, CA

AIRCRAFT VULNERABILITY: A SURVEY OF COMBAT AND PEACETIME EXPERIENCE 37
Mr. Kevin R. Crosthwaite
Director, Survivability/Vulnerability Information Analysis Center (SURVIAC)
Wright-Patterson AFB, OH

A HISTORY OF THE SURVIVABILITY DESIGN OF MILITARY AIRCRAFT 75
Distinguished Professor Robert E. Ball
Naval Postgraduate School
Monterey, CA

AIRLINE SAFETY & SECURITY: AN INTERNATIONAL PERSPECTIVE 90
Captain Peter T. Reiss
Chairman, Security Committee
International Federation of Air Line Pilots' Association
Hudson, NY

VULNERABILITY REDUCTION IN ARMY AVIATION 101
Brigadier General Charles M. Burke, USA
Deputy Commanding General
U.S. Army Aviation Center
Fort Rucker, AL

SURVIVABILITY SYMPOSIUM "ENHANCING AIRCRAFT SURVIVABILITY - A VULNERABILITY PERSPECTIVE" 126
Rear Admiral John M. Johnson, USN
Head, Aviation Plans and Requirements
Office of the Chief of Naval Operations
Washington, DC

PERSPECTIVES ON OPERATIONAL REQUIREMENTS AND VULNERABILITY REDUCTION 133
Major General Frederick McCorkle, USMC
Commanding General
3rd Marine Aircraft Wing, MCAS
El Toro, CA

ENHANCING SURVIVABILITY - AN AIR FORCE PERSPECTIVE 156
Major General Gregory S. Martin, USAF
Director, Operational Requirements
Headquarters, U.S. Air Force
Washington, DC

AIRCRAFT SURVIVABILITY: A LOOK INTO THE CRYSTAL BALL (A COMPOSITE SKETCH) 179
Mr. James F. O'Bryon, Deputy Director
Operational Test and Evaluation (Live Fire Test)
Office of the Secretary of Defense, and Chairman
NDIA Test & Evaluation Division
Washington, DC

OVERVIEW OF STRUCTURAL DAMAGE TOLERANCE HISTORY AND TRENDS 211
Mr. Robert G. Eastin
National Resource Specialist for Fractured Mechanics
Federal Aviation Administration
Lakewood, CA

IMPROVING HUMAN SURVIVABILITY IN AIRCRAFT THROUGH CRASHWORTHINESS TECHNOLOGY: SYMPOSIUM ON ENHANCING AIRCRAFT SURVIVABILITY 231
Mr. Huey D. Carden, Senior Researcher
Structural Mechanics Branch
NASA Langley Research Center
Hampton, VA

COVER LETTER "FIRE SAFETY IMPROVEMENTS THROUGH R&D" (ENCLOSED THREE PAPERS, LISTED BELOW) 294

WATER SPRAY SYSTEM DEVELOPMENT AND EVALUATION FOR ENHANCED POSTCRASH FIRE SURVIVABILITY AND IN-FLIGHT PROTECTION IN CARGO COMPARTMENTS 295

FULL SCALE TEST EVALUATION OF AIRCRAFT FUEL FIRE BURN-THROUGH RESISTANCE IMPROVEMENTS 307

AIRCRAFT FIRE SAFETY 315
Mr. Constantine P. Sarkos, Manager
Fire Safety Section
FAA William J. Hughes Technical Center
Atlantic City Airport, NJ

HARDENING AIRCRAFT AGAINST TERRORIST THREATS 330
Ms. Chantal Joubert, Manager
Aircraft Protection
Advanced Aircraft Program
The Boeing Company
Long Beach, CA

THESIS: EFFECTS OF DIGITAL AVIONICS SYSTEMS ON THE SURVIVABILITY OF MODERN TACTICAL AIRCRAFT 354
Commander Wade D. Duym, USN
Naval Postgraduate School
Monterey, CA

DESIGNING DIGITAL AVIONICS SYSTEMS FOR REDUCED VULNERABILITY 427
Commander Wade D. Duym, USN (Ret)
Manager, Avionics Systems, Engineering Group, Batttelle
Columbus, OH

AIRCRAFT FIRE EXTINGUISHING SOLUTIONS 447
Mr. Glenn E. Harper, Senior Principal Technical Specialist
Advanced Systems & Technology
The Boeing Company
St. Louis, MO

ALTERNATIVES TO HALON: A STATUS REPORT 470
Mr. Mathias L. Kolleck, Manager
Advanced Technologies
Booz-Allen & Hamilton, Inc.
Beavercreek, OH

INTEGRATED SURVIVABILITY ASSESSMENT: MEASURING THE BALANCE.............479
Mr. David H. Hall, Chief Analyst
Survivability Division, Naval Air Warfare Center
Weapons Division and Chairman
Methodology Subgroup, JTCG/AS
China Lake, CA

BALANCING SURVIVABILITY ATTRIBUTES: THE COST OF MISSION SUCCESS........511
Dr. Alex Loewenthal, Manager
Systems Engineering and Balanced Survivability
Lockheed Martin Skunk Works
Palmdale, CA

FLIGHT SYSTEMS' INTEGRATION IMPACT ON AIRCRAFT VULNERABILITY..........534
Mr. Bruce T. Clough, Electrical Engineer
Air Force Research Laboratory and Chairman,
Flight Systems Committee, JTCG/AS
Wright-Patterson AFB, OH

AIR VEHICLES TECHNOLOGY: BETTER PERFORMANCE, REDUCED VULNERABILITY..........558
Colonel Gerald A. Hasen, USAF
Deputy Director, Air Vehicles Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH

PROPULSION CONTROLLED AIRCRAFT: A SAFETY AND SURVIVABILITY ENHANCEMENT CONCEPT..........589
Mr. Frank W. Burcham, Chief
Propulsion Research Branch
NASA Dryden Flight Research Center
Edwards AFB, CA

ROTOCRAFT SURVIVABILITY ADVANCEMENTS THROUGH TECHNOLOGY............612
Mr. Nikolaos Caravasos, Manager
Military Technology, Boeing Defense and Space Group
Rotocraft Division
Philadelphia, PA

COMPOSITE STRUCTURE DESIGNS: LESS VULNERABLE, MORE AFFORDABLE.......632
Mr. William G. Baron, Aerospace Engineer
Air Force Research Laboratory and
Chairman, Structures and Materials Committee, JTCG/AS
Wright-Patterson AFB, OH

AIRCRAFT ACCIDENTS/INCIDENTS: EXTENDING THE VULNERABILITY DATABASE 647
Mr. Michael Meyers, Senior Principal Technical Specialist
The Boeing Company
St. Louis, MO

REDUCING CHEMICAL, BIOLOGICAL, AND RADIOLOGICAL VULNERABILITY THROUGH DESIGN 656
Mr. Gerald J. Burblis, Senior Survivability Analyst
Sikorsky Aircraft Corporation
Stratford, CT

COVER LETTER - ADPA/NSIA ENHANCING AIRCRAFT SURVIVABILITY CONFERENCE IN MONTEREY, CA (ENCLOSED TWO PAPERS, LISTED BELOW) 671

JOINT STRIKE FIGHTER 672
Mr. Daniel B. Arnold, Analyst and Integration Team Leader
Joint Strike Fighter Program
Lockheed Martin Tactical Aircraft Systems
Ft. Worth, TX

SPACE SYSTEM VULNERABILITY TO ORBITAL DEBRIS PENETRATION 697
Mr. Joel E. Williamsen, Structural System Survivability
NASA, Nation Aeronautics and Space Administration
George C. Marshall Space Flight Center
MSFC, AL

LIST OF ATTENDEES FOR THE SYMPOSIUM 714

NOTICE

Enhancing Aircraft Survivability

Combat Survivability Division

National Defense Industrial Association

Monterey, California

21 October 1997

Mission

Combat Survivability Division
National Defense Industrial Association

“ To enhance survivability as an essential element of overall combat mission effectiveness ”

Supporting Goals

- Enhance survivability technology base and information exchange
- Foster innovative solutions to survivability challenges
- Work toward a balanced design approach to survivability
- Maintain survivability as an aircraft design discipline
- Improve battle damage repair capability
- Promote realism in assessments, simulations, testing
- Increase awareness of survivability issues by senior officials

Our Organization

- **All volunteer group from industry, government, and academia**
- **Governed by an Executive Board representative of the broad survivability community**
- **Work accomplished through committees**
  - **Strategic Planning**
  - **Symposium Program (ad hoc for each event)**
  - **Awards**
  - ***Steering***
  - ***Technology Interchange***
  - ***Communications***
  - ***Senior Advisory Council***
- **Welcome participation by friends of survivability, both civil and military-related**
  - **Join the association**
  - **Let us know about your interest**

What We Do

- Symposiums
  - ◇ 1989 – General Survivability
  - ◇ 1990 – Low Observables
  - ◇ 1991 – Battle Damage Repair
  - ◇ 1993 – Transport Aircraft Survivability, Civil and Military
  - ◇ 1994 – Testing for Combat Survivability
  - ◇ 1996 – Impact of Low Observable Technology
  - ◇ 1997 – Vulnerability Reduction Technology

- Future symposiums at Monterey
  - ◇ August 1998 -- Countermeasures & Low Observables: Complementary Capabilities
  - ◇ November 1999 -- General Survivability

- Topical "Quick Looks"
  - ◇ Highly focused one day reviews or workshops
  - ◇ Under consideration

Aircraft Survivability – What Does it Mean?

Department of Defense definition:

“ The capability of an aircraft to avoid or withstand man-made hostile environments without suffering an abortive impairment of its ability to accomplish its designated mission ”

Survivability’s twin elements:

- **Susceptibility Reduction – reducing the probability of hit** [*or internal explosion*]
- **Vulnerability Reduction – mitigating damage in the event of a hit** [*or explosion*]

Survivability Means Different Things to Different People

- Defense suppression
- Signature reduction, stealth
- Countermeasures, decoys, deception
- Locating and acquiring the target
- Stand-off weapons
- Tactics – speed, maneuver, altitude, routing; and training
- Avoiding low altitude during daylight
- Unmanning – using unmanned aerial vehicles and cruise missiles
- Just not going there
- Passenger and baggage screening

- Damage resistance, damage tolerance, armor plate
- Testing
- Battle damage repair, force reconstitution

Isn't survivability about all of these?

A Big Question

Preface:

- **We've come a long way in aircraft survivability in the last 25 years**
- **There is much to take pride in**
- **So, some say, special focus is no longer needed. Why not reallocate scarce resources elsewhere?**

The Question:

" Is a special, disciplined focus on aircraft survivability still needed, since to some people, survivability is already firmly embedded in both the requirements process and aircraft design? "

The right answer:

" Yes ! Special attention is still needed. But, . . . advocates must become more active since much associated with traditional survivability is seen as 'old hat' and not relevant to the challenges of today and tomorrow "

State of Survivability Community and Discipline

Some Observations

- "Corporate memory" is fading
  - Fewer officers with experience in wars against resolute, capable foes
  - Downsizing in industry and government, company mergers, survivability pioneers retiring
- Countermeasures community and general survivability remain largely separate
- Stealth is seen as the answer to most military survivability needs
- Increasing interest by civil aviation in survivability issues, and in fire and explosion safety
- No serious movement to develop a credible, overall survivability assessment capability
- Little activity in vulnerability reduction R&D – despite live fire test law, airline incidents

Civil-Military Aircraft Fire and Explosion Mitigation Project

- **Build on current individual and limited cooperative efforts**
  - **DoD's Next Generation Fire Suppression Program**
  - **FAA Technical Center work**
  - **DoD's Safety and Survivability of Aircraft Initiative, ... and others**

- **Issues to examine:**
  - **Character of fires / explosions and causes of initiation**
  - **Characterization of fuels and other flammable liquids, by type**
  - **Fire detection and suppression systems, explosion mitigation techniques**
  - **Improved modeling and analysis tools for predicting fires and explosions**
  - **Designing aircraft with reduced vulnerability to fire and explosion, ... and others**

- **Participants**
  - **FAA, NTSB, NASA, Europe's Joint Aviation Authorities (JAA)**
  - **Department of Defense components and agencies, NATO member air forces**
  - **Airframe and engine manufacturers, airline companies, universities**

- **Structure like DoD's Integrated High Performance Turbine Engine Tech program (IHPTET)**
  - **Clearly defined technical and timeline goals**
  - **Government-industry partnering**
  - **Stable funding profile**

- **Make project a U.S. national priority, ... and encourage others to join**

Three Worthy Near Term Goals

1. Assessments

   Develop a credible capability to assess the impact of the several contributors to aircraft survivability, thereby facilitating sound design and procurement decisions, and the best use of scarce resources

2. Countermeasures

   Bring the countermeasures and general survivability communities closer together to a point where they are viewed as one

3. Vulnerability Reduction

   Resuscitate the increasingly moribund vulnerability reduction technology base – breathe some life into it! Why not start with the Civil-Military Fire and Explosion Mitigation Project?

PEOPLE ISSUES

Honorable John J. Goglia
Member National Transportation Safety Board

Remarks To The
American Defense Preparedness Association
Monterey, CA
October 21, 1997

Good morning ...

I want to discuss with you this morning the subject of people; how they are affected by the system as well as their influences upon the system.

Today's airplanes are subject to very few critical failure modes. We have nearly eliminated the mechanical causes for accidents. This is traceable to the design requirements of the relevant governmental regulations as well as the specifications of operating organizations and the design skills of manufacturers. We have come a long way in the last 80 years.

But, we are now faced with what I believe is rapidly becoming the dominant element in aviation safety. I am referring to people.

They are affected:

- by man/machine interfaces which influence mechanic, controller and pilot induced errors.
- by relationships between designer and maintenance users.
- by relationships between and among regulators and regulated, and;
- by individual responsibility and accountability

During the past two years in the civil arena we have had an unprecedented number of accidents in which the overwhelming causes appear to be people centered. Consider some recent examples of problems in the cockpit, the tower and in the hanger.

In November,1995 an MD-80 was nearly lost in East Granby, Connecticut. Barely two months later, a DC-9 was nearly lost in Houston Texas. Fortunately there were no serious injuries in either incident; just substantial damage to the aircraft. The principle causative agents in both these incidents are similar - people, procedures and communications.

I am further alarmed at what I believe is a trend for air traffic control induced pilot error. I refer to controllers who issue unreasonable, unwise or uninformed instructions. These instructions involve maneuvering aircraft in ways that simply should not be undertaken.

This is exemplified by a recent ATR 72 accident in Roselawn Indiana; and an Embraer 120 in Monroe Michigan. The common denominator in both these

accidents was that the airplanes were operating in icing conditions for an extended period at slow speeds. The pilots of these aircraft were following instructions from ATC. However, ATC was not aware that their clearances put the airplanes at risk and the pilots did not inform the controllers they were in icing. Again - people, procedures and communications.

Between 1961 and mid 1995 there were over 32 accidents related to maintenance error; approximately one per year. Yet, from mid 1995 until the summer of 1996 we had 5 accidents directly related to maintenance error. Something is definitely wrong. I suspect - people, procedures communications and design.

Finally, in 1994 a structural survey of retired transport aircraft was done. This involved an assessment of the adequacy of structural repairs accomplished upon them during their working lives. The results were alarming. Both engineering and the quality of accomplishment of the repairs was disturbingly inadequate. Again - people, procedures, communications and design appear to be underlying culprits.

The common denominator among all these accidents is that the human in the loop fails for a variety of reasons. We have more than 40 years of human factors research into the flight deck, a little less than ten in maintenance and next to none in the engineering design arena. It's obvious that we have a way to go before we understand the human factors issues. People related accidents continue to occur.

The elements to solving much of the people problem are simple.

Control the information explosion which plagues the cockpit and the hanger when digital airplanes are involved. Aggressively apply existing, proven human factors techniques to both; but particularly to the long neglected maintenance and design disciplines.

Bring controllers into the pilot training process so that both develop a better understanding of each others operating environments.

Design for maintenance.

Maintainability is not just ergonomics or accessibility. It includes the management of failure to keep the airplane available while concurrently keeping it airworthy. Engineering needs to be closer to maintenance, both at the manufacturer and the airline to accomplish this end. Designers and maintainers must communicate.

This is radical thinking. It is amazing what involvement the user of the product with the designer of the product will yield. Original designs become more appropriately directed toward;

- reducing change error and rework
- reducing maintenance related error
- improving equipment reliability and hence its' availability to the schedule and;
- reducing maintenance costs.

This means maintenance must be at the design table as an equal to the demands of drag, weight and producability. But in turn maintainers must concern themselves with the limitations imposed upon designers.

Engineering designers must spend time at the maintenance table. Young engineers, as a part of their training, should be exposed to the problems and concerns of the entire maintenance community including maintenance engineering, line and hanger maintenance, planning and task performance. This includes a healthy infusion of practicality to temper academic correctness.

The relationships between government and industry clearly affect people. We are all a part of one global aviation family.

Design, operating and regulatory issues **must** be debated. But, put principles before personalities. Let the debate be among peers not adversaries. We must stop bickering and sniping at each other - industry, operators and regulators. I agree heartily with the principles of working together.

Finally people have their own effect upon safety.

Aviation has long held responsibility and accountability to be core values. It is an industry built upon trust. Each of us expects, in fact, demands, that every discipline do his/her job. This embraces responsibility and accountability.

However, something has happened within our operating organizations. I think one such "something" is a clear change in the employee makeup of this industry.

Employees hired since the mid 80's - one major airline calls it the "Class of 1986," appear to come into the industry without a dedication to aviation.

They only accept employment because it's a job with better benefits than many others. Thus we see today, people who accomplish their work blindly without thinking of the consequences of their actions, or who do not challenge the system if they believe it is wrong. They are part of a culture in which few, if any, feel accountable for their actions, except for the bottom line or personal agendas. The consequences are disturbing.

For example.

Some of you may believe that an FAR Part 145 repair station certificate is an automatic index of quality and expertise. This is not always the case.

This became painfully clear after the Everglades accident. We found that up to 70% of the employees at the repair station associated with the accident were not certified technicians. Many had minimal training. Under these circumstances an extremely good quality surveillance system would be assumed to be in place. But it wasn't.

This had a serious negative effect upon the work product and safety.

It is the true people problem.

We need, many believe, a return to a culture of individual responsibility and accountability for behavior within our system if we hope to ever get a handle on all our safety problems.

In conclusion, safety involves people --- their procedures communication, designs and dedication. I believe the solutions are simple. **It is nothing more than a reestablishment of cooperation and individual responsibility.**

Thank you...

HUGHES AIRCRAFT

ADPA/NSIA Aircraft Survivability Symposium

Vulnerability Reduction:
Critical For Today and Tomorrow

presented by
W. C. Bowes
Hughes Aircraft Company

VULNERABILITY REDUCTION
CRITICAL FOR TODAY AND TOMORROW

THANK YOU FOR THE KIND INTRODUCTION, MR. VICE, ADMIRAL EVANS, GENERAL BURKE, ADMIRAL GORMLEY, MR. FRANCIS, MR. MUTZELBURG, DISTINGUISHED GUESTS, MEN AND WOMEN OF THE SURVIVABILITY COMMUNITY, LADIES AND GENTLEMEN ----- I CAN NOT TELL YOU HOW HONORED I AM TO HAVE BEEN INVITED TO SPEAK TO THIS SYMPOSIUM.

I CONGRATULATE YOU ON YOUR CHOICE OF LOCATIONS TO HOLD THIS SYMPOSIUM. NAVY POSTGRADUATE SCHOOL, MONTEREY, CA ----THE PLACE WHERE SO MANY OF US HAVE GAINED AN APPRECIATION AND UNDERSTANDING OF SURVIVABILITY FROM PROFESSOR ROBERT BALL, AND THE BIRTHPLACE OF THE BIBLE FOR THIS DISCIPLINE— HIS TEXT BOOK <u>THE FUNDAMENTALS OF AIRCRAFT COMBAT SURVIVABILITY ANALYSIS AND DESIGN.</u>

YOU HAVE COME A LONG WAY, AND THE SUCCESSES OF YOUR PRODUCTS IN DESERT STORM HAVE PROVEN THE VALUE OF THE EXPERTISE THAT YOU HAVE PROVIDED TO THE AIRCRAFT DESIGN COMMUNITY.

THE DEFENSE BUDGET HAS DECLINED 40% IN THE PAST EIGHT YEARS, BUT THE PROCUREMENT BUDGET HAS DECLINED OVER SIXTY PERCENT. WE ARE BUYING REPLACEMENT HARDWARE, AIRCRAFT, SHIPS, TANKS, TRUCKS AT A RATE THAT WILL NOT COME CLOSE TO SUSTAINING THE SIZE OF THE FORCE STRUCTURE THAT STUDY AFTER STUDY SHOWS OUR NATION NEEDS. YOU ALL KNOW TOO WELL THIS IS A TIME OF CHANGE UNLIKE ANY OTHER.

I'M REMINDED OF THE STORY OF THE TRUCK DRIVER GOING DOWN A STEEP WINDY MOUNTAINSIDE ROAD-----

LET GO; TRUST ME. IS THERE ANYONE ELSE UP THERE WHO CAN HELP ME?

LIKE MY LITTLE STORY, THE ENVIRONMENT TODAY IS SAYING TRUST ME, LET GO ----- YCJ CANNOT GO ON DOING THINGS THE SAME WAY. IN MY BRIEF REMARKS THIS MORNING I HOPE TO LEAVE YOU WITH SIX CHALLENGES:

1. THE SURVIVABILITY WORLD NEEDS IMPROVED MODELING AND SIMULATION, AND YOU NEED TO APPLY IT EARLIER AND MORE OFTEN IN THE DESIGN PROCESS.

2. GREATER UNDERSTANDING NEEDS TO BE ACHIEVED OF YOUR DISCIPLINE THROUGHOUT THE DOD COMMUNITY.

3. THE SURVIVABILITY COMMUNITY NEEDS TO BE BETTER INTEGRATED WITH THE EW, RELIABILITY AND SYSTEMS SAFETY COMMUNITIES.

4. A SYSTEMS OF SYSTEMS PERSPECTIVE NEEDS TO BE INTEGRATED INTO SURVIVABILITY ANALYSIS

5. A HIGH LEVEL DOD CHAMPION IS NEEDED TO SUPPORT THE INITIATIVES OF THE SURVIVABILITY COMMUNITY.

BUT, TO MAKE THE CHANGES AND IMPROVEMENTS I HAVE LISTED "YOU CAN'T JUST KEEP DOING WHAT YOU'VE ALWAYS BEEN DOING. OR YOU'LL GET WHAT YOU'VE ALWAYS GOTTEN

LET ME SHOW YOU A COUPLE OF VIEWGRAPHS THAT MAKE THE POINT OF HOW WE ARE NOT BUYING AIRCRAFT AT A RATE SUFFICIENT TO SUSTAIN THE FORCE STRUCTURE.

THESE NAVY CHART SHOWS THAT THE NUMBER OF AIRCRAFT IN THE INVENTORY HAS DECLINED, BUT IS PLANNED TO REMAIN RELATIVELY STEADY. THE NEXT CHART DRAMATICALLY SHOWS THE DECLINE IN NUMBER OF AIRCRAFT BOUGHT PER YEAR.

THE NEXT CHART SHOWS HOW LONG TACTICAL AIRCRAFT ARE REMAINING IN THE INVENTORY. THE MESSAGE IS LOUD AND CLEAR--- WE ARE NOT PROCURING AIRCRAFT AT A HIGH ENOUGH RATE.

THIS HAS SIGNIFICANT IMPLICATIONS FOR THE WORLD OF SURVIVABILITY, AND MOST DEFINITELY VULNERABILITY REDUCTION. WE ARE DEPENDING ON USING OUR AIRCRAFT FOR LONGER PERIODS OF TIME, IN PEACE TIME AND IN WAR. AND WE EXPECT THEM TO SURVIVE WHEN USED IN ANGER.

THE DEBATES RAGE OVER THE RIGHT BALANCE OF CRUISE MISSILES, STAND OFF WEAPONS, STEALTH AIRCRAFT, AND IN THE FUTURE UNINHABITED COMBAT AIR VEHICLES.
BUT IN EACH OF THESE VEHICLES THE NEED FOR SUSCEPTABILITY AND VULNERABILITY REDUCTIONS LOOM HIGH, AND THE COST OF EACH OF THESE SYSTEMS DEMANDS THAT SURVIVABILITY BE AN UPFRONT DESIGN CONSIDERATION.

ACQUISITION REFORM IS MOVING VERY WELL, AND UNDER DR. GANSLER I FULLY EXPECT THE RATE OF POSITIVE CHANGE TO CONTINUE. COST AS AN INDEPENDENT VARIABLE IS THE BENCHMARK THAT MUST BE USED TO DESIGN AND DEVELOP OUR SYSTEMS FOR THE FUTURE. I REALIZE THAT THE UNDERSTANDING AND SUCCESSFUL USE OF CAIV IS SPOTTY, BUT I CAN ASSURE YOU THAT DOD'S COMMITMENT TO MAKE THIS SUCCEED IS STRONG--- AND SURVIVABILITY MUST BE PART OF THE COST BENEFIT ANALYSIS TRADES.

OTHER ACQUISITION REFORM INITIATIVES INCLUDE GOING TO PERFORMANCE SPECS, THE ABSENCE OF MIL SPECS, AND THE INCREASED USE OF COMMERCIAL CONTENT IN ALL OF OUR SYSTEMS.

IF YOU ARE NOT WORRIED ---- YOU BETTER WAKE UP. WHEN THE COST TRADES ARE MADE, AND THE COMMERCIAL CONTENT APPLIED, ARE YOU CONFIDENT THAT THE SURVIVABILITY DISCIPLINE WILL HAVE A SEAT AT THE DECISION TABLE?

WHEN THE TEST PLAN IS CREATED AND THE LIVE FIRE TEST PROGRAM DEVELOPED, WILL IT BE AFFORDABLE, OR WILL IT BREAK THE AFFORDABILITY BANK OF THE PROGRAM?

THOSE QUESTIONS SHOULD CONVINCE YOU THAT THE TIME IS NOW TO FIND MORE AFFORDABLE WAYS TO KEEP SURVIVABILITY AT THE FRONT OF THE DECISION PROCESS. IT IS FAR TOO LATE WHEN THE SYSTEM FAILS A LIVE FIRE DEMO OR A SURVIVABILITY TEST TO MAKING THE NEEDED DESIGN CHANGES.

WE NEED A BETTER APPROACH TO MODELING AND SIMULATION. THE JTCG (AS) HAS BEEN VALIANTLY WORKING FOR THE PAST 10 YEARS, IN WHICH I'VE BEEN SOMEWHAT INVOLVED, IN THE VV&A OF A STANDARD SET OF SURVIVABILITY MODELS. THE GOOD NEWS IS THAT THE OSD FUNDING FOR THIS VITAL EFFORT APPEARS TO BE GETTING SUPPORT, ALBEIT ONLY AT THE RELATIVELY LOW LEVEL OF ABOUT $ 7 MILLION A YEAR.

SIX YEARS AGO I BECAME INVOLVED IN TRYING TO FIND A WAY TO CREATE A PANEL OF OUR NATION'S FOREMOST SURVIVABILITY EXPERTS TO REVIEW EVERY MAJOR PROGRAM'S PROPOSED M&S PLAN FOR SURVIVABILITY ANALYSIS. THE EXPECTATION WAS THAT A CONSISTENT SET OF MODELS WOULD BE UTILIZED, LESSONS LEARNED WOULD BE SHARED FROM PROGRAM TO PROGRAM, THE FIDELITY AND UTILITY OF MODELS WOULD IMPROVE, THE DOLLARS SPENT ON M&S IN BOTH INDUSTRY AND THE GOVERNMENT WOULD BE MORE FOCUSED AND THEREBY MORE EFFICIENTLY USED, AND LASTLY, AND MOST IMPORTANTLY, WE

WOULD AVOID THE COSTLY LATE IN THE GAME DISPUTES OVER THE SELECTION OF THE MODELS USED OR THE VALIDITY OF THE RESULTS ACHIEVED.

WHEN I WAS ASKED TO SPEAK AT THIS SYMPOSIUM, I INQUIRED AS TO THE STATUS OF THE EFFORT TO CHARTER A BODY OF "EXPERTS IN SURVIVABILITY" TO VALIDATE THE M&S PLANS FOR THE SURVIVABILITY ANALYSIS OF AIRCRAFT SYSTEMS. I WAS TOLD THAT IT IS BASICALLY JUST WHERE IT WAS WHEN I LEFT DOD, OR WHEN I DEPARTED THE JACG IN MAR OF 95.

CHANGE IS OFTEN DIFFICULT TO BRING ABOUT, BUT I HAVE NEVER SEEN ANYTHING THAT SEEMED SO LOGICAL TO DO, BE SO DIFFICULT TO BRING ABOUT.

UNLESS THIS COMMUNITY FINDS A WAY TO GAIN SERVICE AND OSD ACCEPTANCE, AND YES APPROVAL, OF THE M&S PLANS DEVELOPED FOR SYSTEMS BEFORE THE EFFORTS ARE EXPENDED RUNNING THE SCENARIOS AND COMPLETING THE ANALYSIS, WE WILL CONTINUE TO INVITE COSTLY DISPUTES, THAT DELAY PROGRAMS, ARGUING OVER THE SELECTION OF MODELS AND SCENARIOS IN ASSESSING A SYSTEM'S SURVIVABILITY.

I'M REMINDED OF THE STORY OF THE THREE DOD COMPTROLLERS WHO DIED, AND TO ST. PETER'S AMAZEMENT WENT TO HEAVEN AND WERE STANDING OUTSIDE THE PEARLY GATES. --------
"THEY'RE GONE" ALL THREE ARE GONE? "NO, THEY HAVE TAKEN THE PEARLY GATES"

THERE'S A MESSAGE IN THAT STORY, BECAUSE THE COMPTROLLERS HAVE NO CHOICE BUT TO SPREAD THE LIMITED DEFENSE DOLLARS TO COVER ALL NEEDS. AND THAT MEANS NOT HAVING ENOUGH IN MOST PROGRAMS TO DO ALL THAT IS NEEDED TO BE DONE.

AND THIS GETS ME TO MY **SECOND POINT. SURVIVABILITY IS A DISCIPLINE THAT IS NOT WELL UNDERSTOOD**. YES, PEOPLE UNDERSTAND RADAR SIGNATURE AND THE ADVANTAGES OF STEALTH, AND THE NEEDS FOR ELECTRONIC COUNTERMEASURES. BUT VERY FEW PEOPLE APPRECIATE, NOR DO THE REQUIREMENT SETTERS EVEN SET REQUIREMENTS FOR VULNERABILITY.

THE LIVE FIRE TEST LAW WAS NEEDED WHEN IT WAS ENACTED. INADEQUATE ATTENTION WAS BEING PAID TO VULNERABILITY IN THE DESIGN OF OUR SYSTEMS. BUT I DO BELIEVE THAT DOD HAS RECEIVED THE MESSAGE, AND VULNERABILITY IS A STRONG DESIGN CONSIDERATION IN ALL OF OUR NEW SYSTEMS.

BUT IT IS TIME FOR A MAJOR REASSESSMENT OF HOW THE LIVE FIRE TEST LAW IS BEING APPLIED. WE SIMPLY CANNOT AFFORD TO DO FULL SCALE LIVE FIRE TESTS ON ALL PLATFORMS. THERE ARE EXAMPLES OF SUCCESSFUL APPLICATION OF THE LAW, SUCH AS THE V-22. WHERE SELECTED MAJOR COMPONENT TESTS ARE BEING CONDUCTED, AND AN ENTIRE VEHICLE WILL NOT BE USED FOR THE LIVE FIRE TEST.

HOWEVER, THE V-22 IS NOT THE GENERAL RULE. WE NEED A BETTER SET OF MODELS FOR VULNERABILITY ANALYSIS. ONE CAN NEVER USE M&S FORD THE ENTIRE VULNERABILITY ANALYSIS, BUT SMART M&S CAN BE USED IN CONJUNCTION WITH COMPONENT AND COUPON TESTS TO GREATLY REDUCE THE COST OF A LIVE FIRE TEST PROGRAM, WITH LITTLE RISK IN NOT CORRECTLY UNDERSTANDING THE VULNERABILITY OF THE SYSTEM.

BUT TO BRING ABOUT ANY CHANGE, YOU NEED TO HAVE UNDERSTANDING AMONG THE DECISION MAKERS, OR THEY WILL BE UNWILLING TO GO FORWARD ASKING TO CHANGE A LAW OR SEEK A WAIVER. SO I REITERATE THE POINT ON THE NEED TO GET INCREASED UNDERSTANDING, ESPECIALLY OF THE VULNERABILITY PART OF SURVIVABILITY, AMONG THE DECISION MAKERS IN DOD.

THE THIRD POINT:

INTEGRATION OF SURVIVABILITY WITH THE EW COMMUNITY IS A MUST. WE HAVE BEEN TALKING ABOUT THIS FOR YEARS, BUT THE NEED IS GREATER NOW THAN EVER BEFORE.

SIGNATURE REDUCTION HAS TAKEN ENORMOUS STRIDES AND HAS BEEN A BIG BOOST FOR SURVIVABILITY. BUT THIS HAS HIGHLIGHTED THE NEED TO LOOK AT THE TOTAL AIRCRAFT SOLUTION TO SURVIVAL.

THIS CHART SHOWS WHAT I CALL THE SURVIVABILITY ANALYSIS FUNNEL. FROM MISSION PLANNING, SUPPORT ASSETS, THE INHERENT SIGNATURE OF THE VEHICLE, THE SMART USE OF RWR AND FLYING THE ROUTE, THE APPLICATION OF ECM, TOWED DEVICES AND EXPENDABLES, AND THEN IF HIT, THE VULNERABILITY OF THE PLATFORM.

YOU HAVE ALL SEEN VERSIONS OF THIS BEFORE. BUT IT THIS COMMUNITY'S RESPONSIBILITY TO HELP THE DECISION MAKER AND THE SYSTEM DESIGNER IN MAKING THE RIGHT TRADES.

IN FACT IT REQUIRES MORE THAN JUST INTEGRATING THE EW AND SURVIVABILITY COMMUNITIES. THE RELIABILITY COMMUNITY AS WELL AS THE SYSTEM SAFETY COMMUNITY MUST BE INTEGRATED INTO YOUR DESIGN PROCESS. I TRUST THAT THE INCREASED USE OF IPTS THROUGHOUT THE INDUSTRY IS MAKING THIS EASIER THAN EVER BEFORE.

THE DESIGN DECISIONS MADE TO IMPROVE RELIABILITY VERY OFTEN SIGNIFICANTLY IMPROVE SURVIVABILITY. TAKE THE RECONFIGURABLE CENTRAL PROCESSOR THAT MY COMPANY HUGHES HAS DESIGNED FOR THE F-22.

OR THE DIGITAL FLIGHT CONTROL SYSTEM AND ITS RECONFIGURABLE CAPABILITIES THAT ARE RESIDENT ON THE F/A-18 TODAY AND WERE SUCCESSFULLY DEMONSTRATED DURING DESERT STORM.

THE ROBUST ELECTRONIC DESIGNS WE ARE LOOKING AT FOR FUTURE SYSTEMS HAVE GRACEFUL DEGRADATION BUILT IN. FROM A VULNERABILITY STAND POINT THAT MEANS BEING ABLE TO SUSTAIN DAMAGE BUT CONTINUE TO OPERATE IN ORDER TO SUCCESSFULLY COMPLETE THE MISSION.

SYSTEM REDUNDANCY, GRACEFUL DEGRADATION ARE BEING DRIVEN BY THE NEED TO IMPROVE RELIABILITY AND DECREASE LIFE CYCLE COST. TO DO THIS SMART REQUIRES CLOSE INTEGRATION OF THE SURVIVABILITY, RELIABILITY, SYSTEMS SAFETY, FLIGHT CONTROL, PROPULSION, FUELS, AND EW COMMUNITIES.

UP UNTIL THIS POINT WE HAVE SPOKEN ABOUT THE SURVIVABILITY AND VULNERABILITY ENHANCEMENT OF A SINGLE PLATFORM. WE NEED TO **EXTEND OUR VIEW BEYOND THE INDIVIDUAL PLATFORM AND LOOK AT SURVIVABILITY FROM A SYSTEMS OF SYSTEMS PERSPECTIVE.**

WE DO NOT NEED THE FULL CAPABILITY, INCLUDING THE ABSOLUTE END ALL SURVIVABILITY, IN EVERY PLATFORM. OUR NATION SIMPLY CANNOT AFFORD THE PRICE, UNLESS WE WANT AN AVIATION CAPABILITY WITH VERY FEW AIRCRAFT.

TODAY A SIGNIFICANT EFFORT IS CORRECTLY BEING APPLIED INTO MAKING OUR WEAPONS SURVIVABLE. THE SAME DESIGN PROCESS THAT IS USED FOR MANNED PLATFORMS APPLIES.

COST TRADES NEED TO BE MADE, AND THIS COMMUNITY HAS THE TOOLS THAT NEED TO BE INCORPORATED INTO THE SYSTEMS OF SYSTEMS LOOKS THAT SHOULD BE USED IN CONJUNCTION WITH COST AS AN INDEPENDENT VARIABLE FOR EACH SYSTEM WE PROCURE.

LIVING WITHIN THE PREDICTED BUDGETS OF THE FUTURE, AND SUSTAINING A FORCE STRUCTURE OF THE SIZE OUR NATION CONTINUES TO REAFFIRM ITS NEED FOR, REQUIRES THAT THE SYSTEM OF SYSTEM PERSPECTIVE BE APPLIED TO DETERMINE THE CAPABILITIES NEEDED IN EACH OF OUR WEAPON SYSTEMS.

THE LAST POINT I'D LIKE TO LEAVE YOU WITH IS THE ABSOLUTE **NEED TO FIND A TRUE CHAMPION, AT A VERY SENIOR LEVEL, FOR SURVIVABILITY IN DOD**.

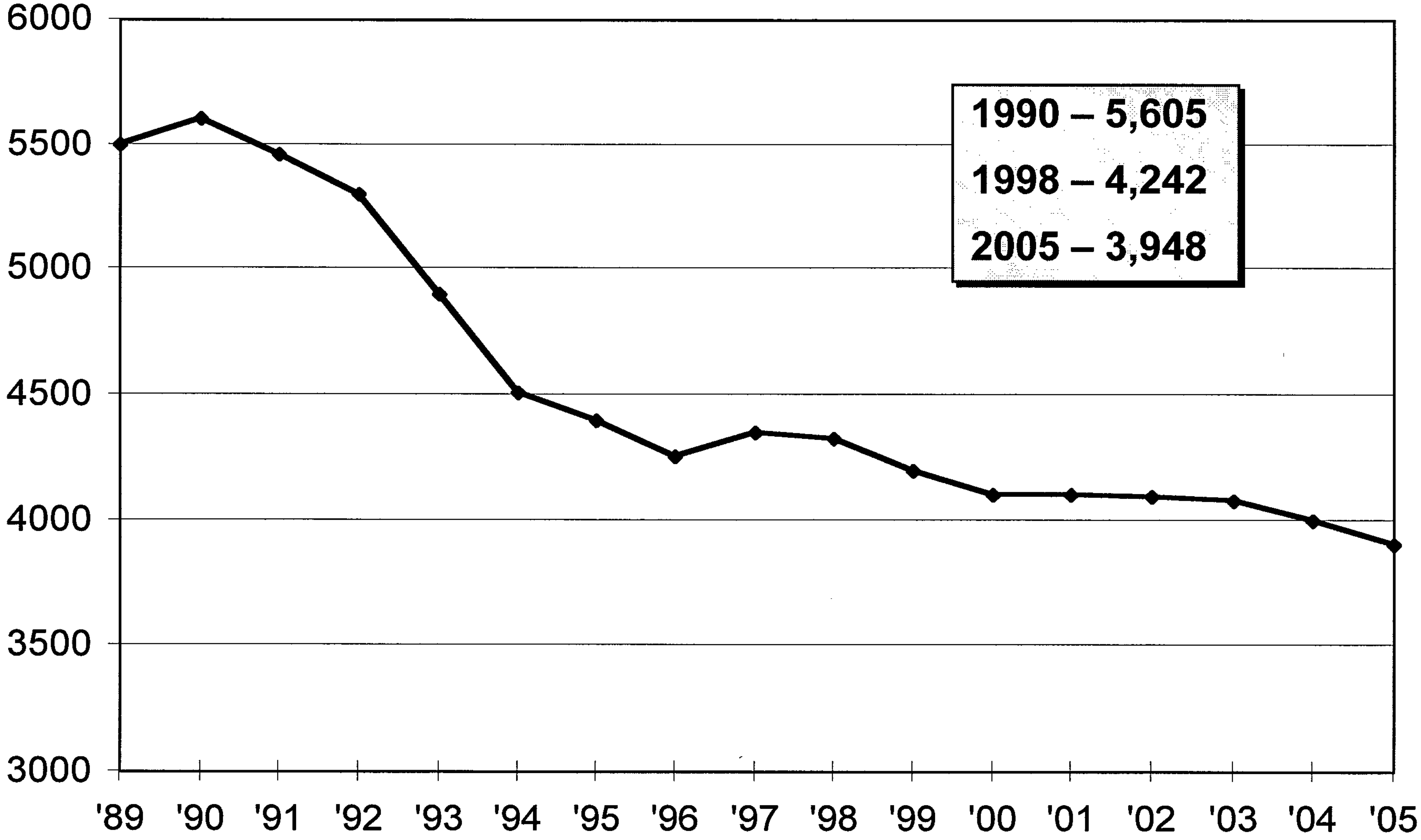
THE CHANGES THAT DOD IS UNDERGOING DEMAND THAT THE VERY IMPORTANT DISCIPLINE OF SURVIVABILITY HAVE A SPOKESPERSON WHO HAS THE UNDERSTANDING AND WILL MAKE THE COMMITMENT TO SUPPORT THE SMART THINGS THAT NEED TO BE DONE TO KEEP SURVIVABILITY AT THE HEAD TABLE AS AN AFFORDABLE AND VITAL DISCIPLINE FOR THE DESIGN OF ALL OF OUR AIR SYSTEMS.

IN CONCLUSION, I TALKED ABOUT SIX CHALLENGES AND NEEDS. OR ACTIONS THAT NEED TO BE TAKEN:

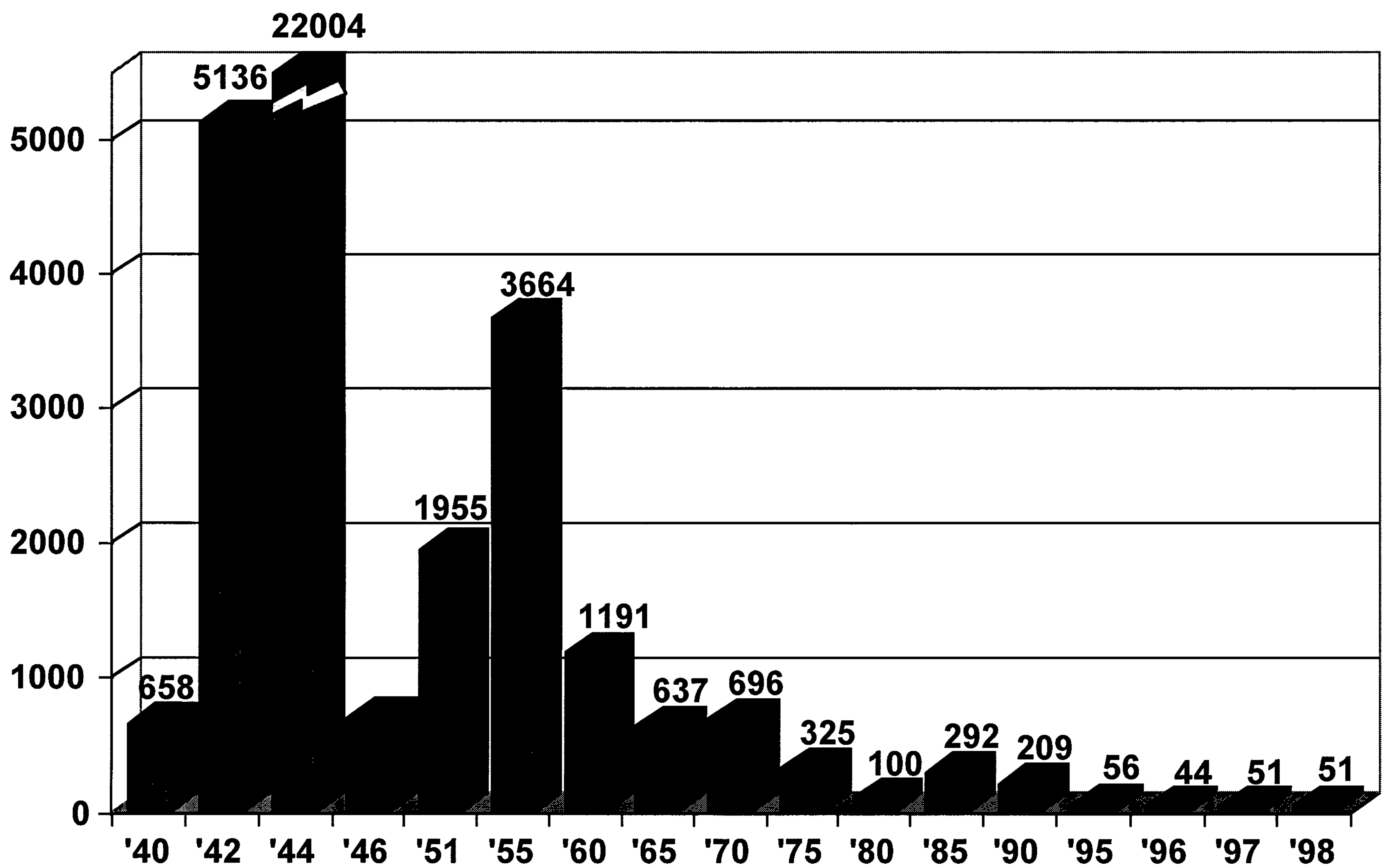
1. YOU NEED MAJOR IMPROVEMENTS TO THE ENTIRE APPROACH FOR M&S FOR SURVIVABILITY
2. YOU NEED TO GET MUCH GREATER UNDERSTANDING OF YOUR DISCIPLINE TO ALL OF THE DECISION MAKERS IN THE ACQUISITION PROCESS—IN BOTH GOVERNMENT AND INDUSTRY
3. YOU NEED TO INTEGRATE THE EW COMMUNITY WITH SURVIVABILITY, AS WELL AS RELIABILITY AND SYSTEMS SAFETY.
4. YOU NEED TO ADD A SYSTEMS OF SYSTEMS PERSPECTIVE TO SURVIVABILITY ANALYSIS
5. AND LASTLY, YOU NEED A HIGH LEVEL SURVIVABILITY CHAMPION WITHIN THE DOD.

THANK YOU FOR YOUR ATTENTION AND FOR GIVING ME THE OPPORTUNITY TO TALK TO YOU THIS MORNING. I'D BE PLEASED TO ANSWER ANY QUESTIONS.

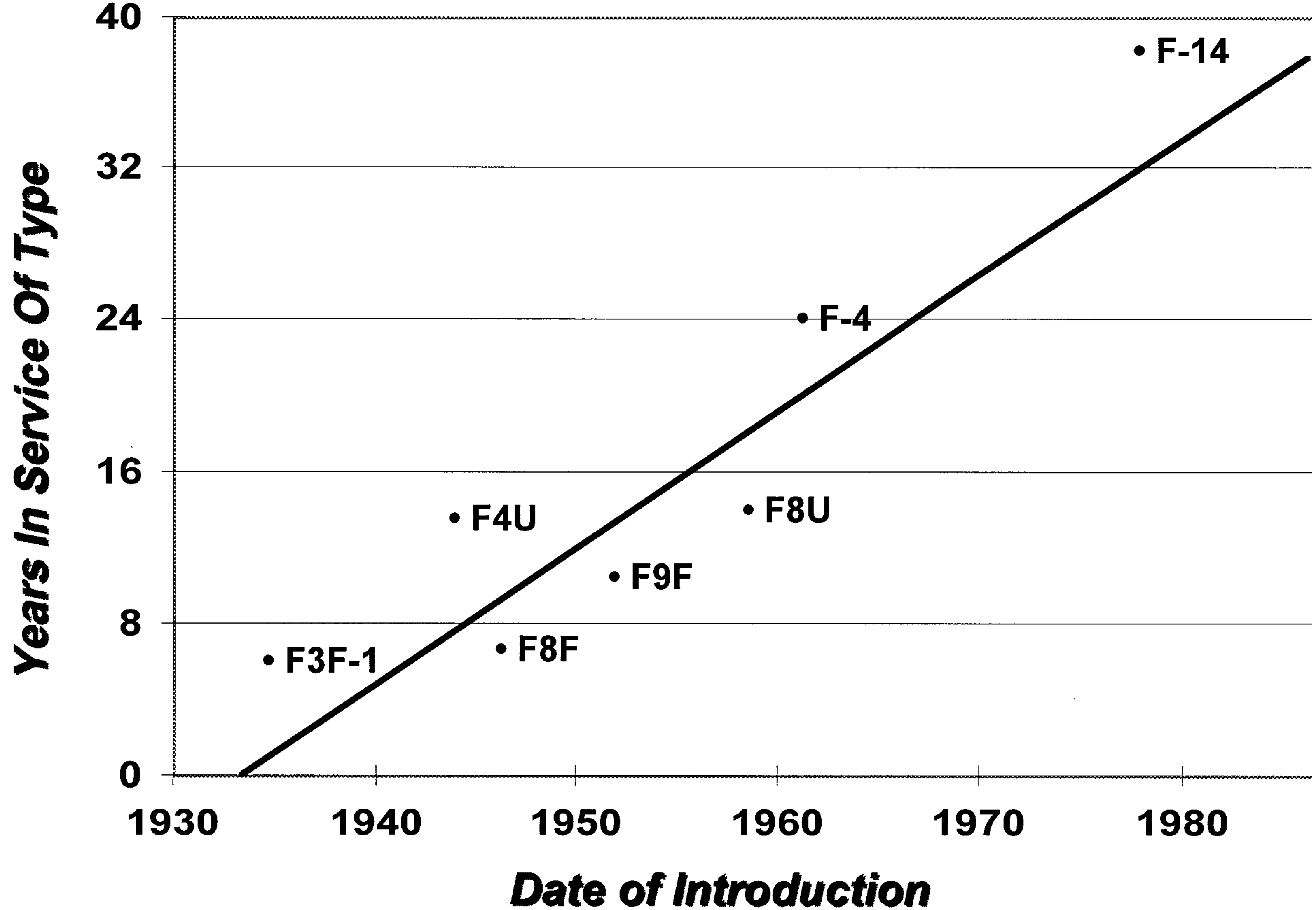
Navy/Marine Corps Aircraft Inventory



Number of Navy Aircraft Accepted Per Year



Fighters Decade of Introduction



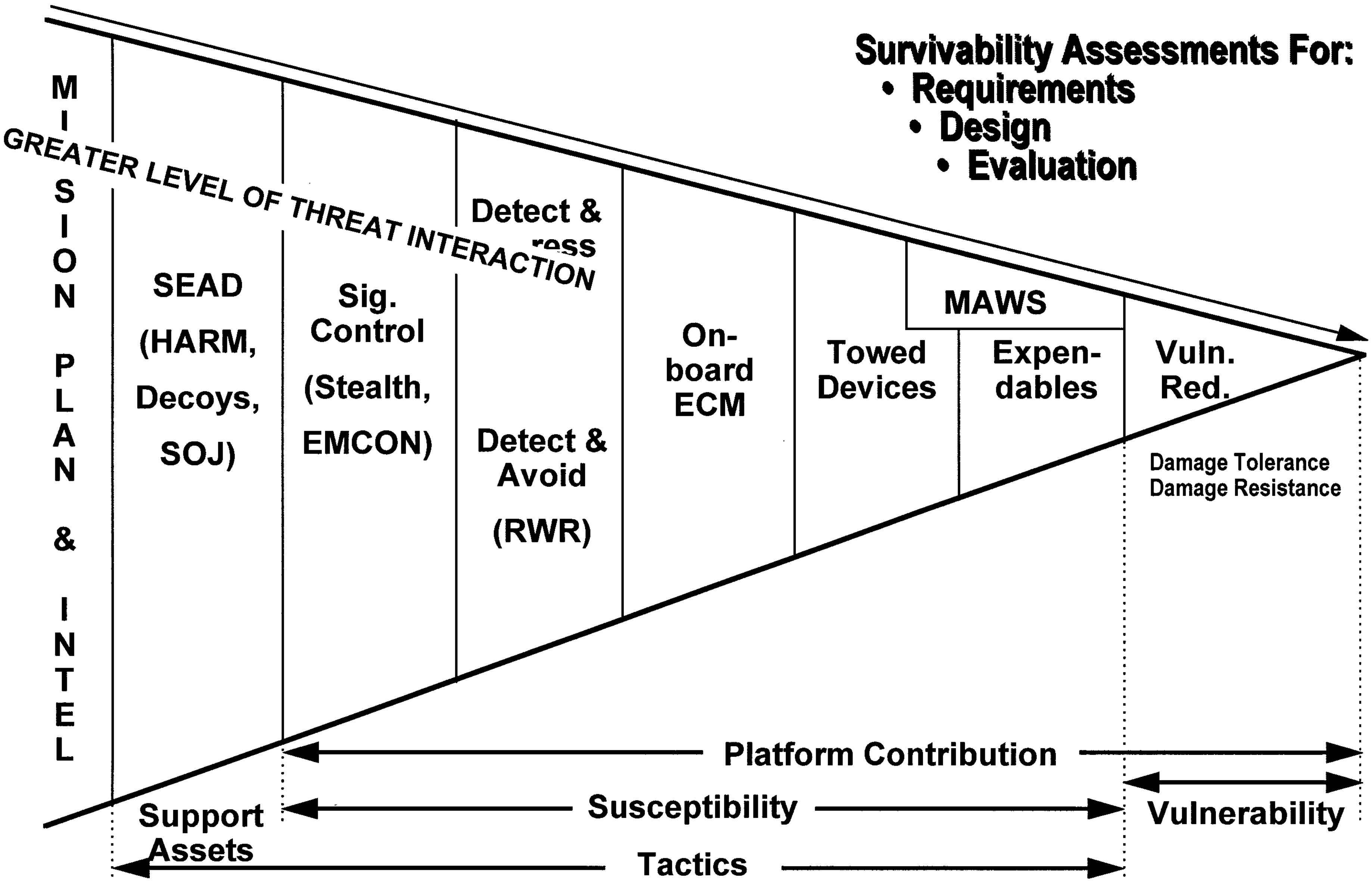
Survivability Challenges & Needs

HUGHES AIRCRAFT

1. Improved and affordable M&S
2. Greater understanding of survivability discipline
3. Integration with EW and Reliability communities
4. System of Systems perspective
5. A high level Survivability Champion

The Survivability Assessment Funnel

HUGHES AIRCRAFT



Aircraft Vulnerability: A Survey of Combat and Peacetime Experience

DEFINITIONS

SURVIVABILITY: THE CAPABILITY OF AN AIRCRAFT TO AVOID OR WITHSTAND A MAN-MADE HOSTILE ENVIRONMENT WITHOUT SUSTAINING AN IMPAIRMENT OF ITS ABILITY TO ACCOMPLISH ITS DESIGNATED MISSION

SUSCEPTIBILITY: THE DEGREE TO WHICH A DEVICE, EQUIPMENT, OR WEAPONS SYSTEM IS OPEN TO EFFECTIVE ATTACK DUE TO ONE OR MORE INHERENT WEAKNESSES

VULNERABILITY: THE CHARACTERISTICS OF A SYSTEM WHICH CAUSES IT TO SUFFER A DEFINITE DEGRADATION (INCAPABILITY TO PERFORM THE DESIGNATED MISSION) AS A RESULT OF HAVING BEEN SUBJECTED TO A CERTAIN LEVEL OF EFFECTS IN AN UNNATURAL (MAN-MADE) HOSTILE ENVIRONMENT

REF: MIL-STD-2089

EQUATIONS

$$P_S = 1 - P_K$$

$$P_S \quad = \quad 1 \quad - \quad (P_H) \quad (P_{K/H})$$

SURVIVABILITY = 1 - (SUSCEPTIBILITY) (VULNERABILITY)

- TACTICS
- SIGNATURE REDUCTIONS
- COUNTERMEASURES
- VEHICLE PERFORMANCE
- DEFENSE SUPPRESSION
- THREAT DEFINITION

- DAMAGE TOLERANCE
- DAMAGE RESISTANCE

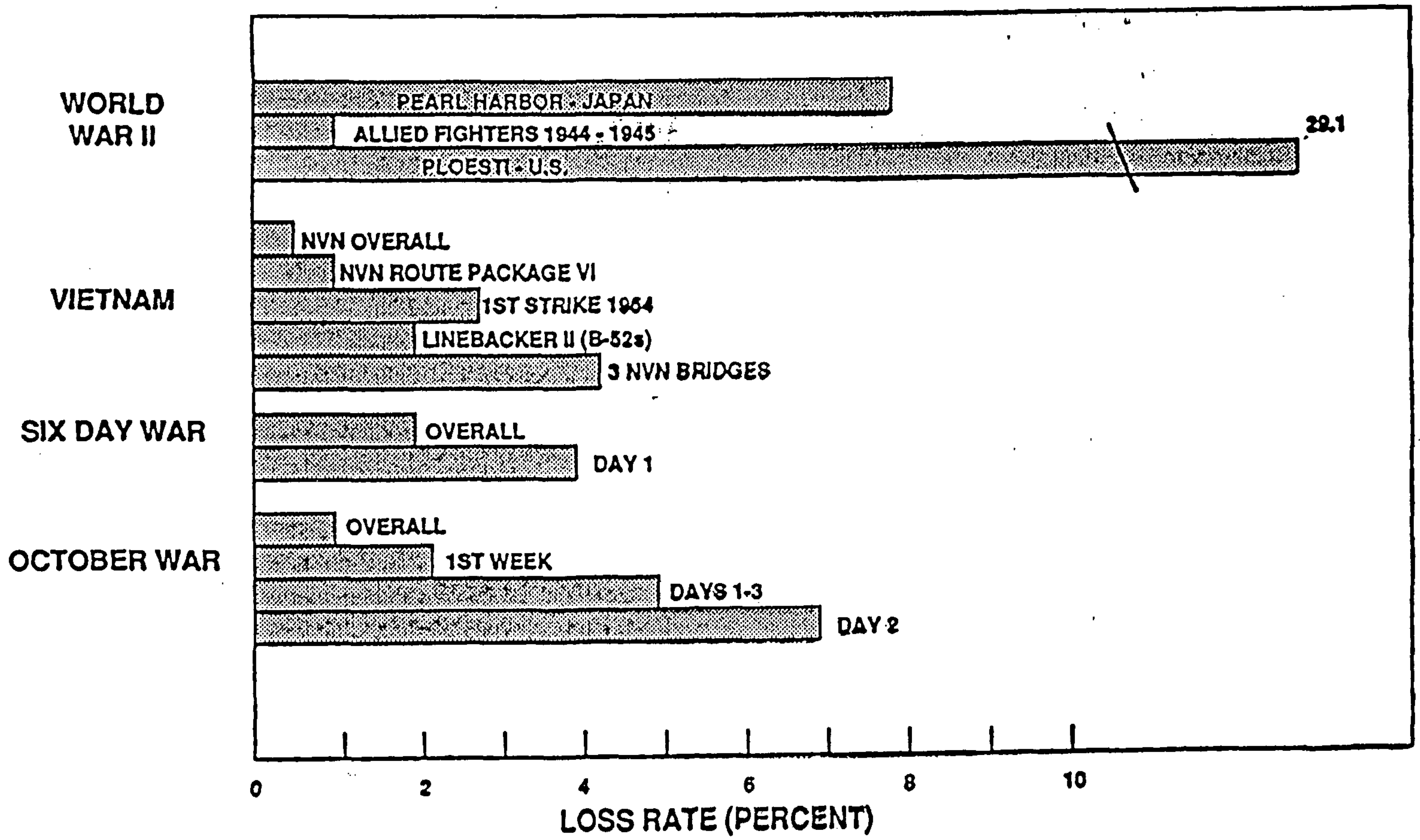
HISTORICAL ATTRITION

MINIMUM ACCEPTABLE SURVIVABILITY OFTEN KEYED TO DURATION OF ENGAGEMENT

- INDIVIDUAL RAIDS MAY EXPERIENCE HIGH LOSS RATES - ACCEPTABLE IF MISSION CRITICAL
- SHORT CONFLICT - ATTRITION MANAGED TO PRESERVE FORCE UNTIL RESUPPLY
- LONG CONFLICT - ACCEPTABLE ATTRITION IS A FUNCTION OF NATIONAL ECONOMY AND THE WILL TO FIGHT

OVERVIEW

HISTORICAL MANNED AIRCRAFT ATTRITION RATES



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HISTORICAL LOSS DATA

WORLD WAR II
KOREA
SOUTHEAST ASIA
FALKLANDS
GRENADA
LIBYA
DESERT STORM

OVERVIEW

UNCLASSIFIED

SIMPLE CALCULATIONS - THEORY (U)

$$P_S = 1 - [P_H * P_{K/H}]$$

P_S	P_H	$P_{K/H}$
SURVIVABILITY	SUSCEPTIBILITY NUMBER OF A/C HIT NUMBER OF EXPOSURES COMPUTE RATIO	VULNERABILITY NUMBER OF A/C KILLED NUMBER OF A/C HIT COMPUTE RATIO

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OVERVIEW

THE REALITY OF IT ALL (U)

- GETTING THE DATA - WARFIGHTERS VS HISTORIANS
  - SEA SPECIALTY TEAMS
  - DESERT STORM EXPERIENCE
- MANY COLLECTORS - MANY STANDARDS
  - DATA ARE ALWAYS MISSING
  - APPLES MAY BE MIXED WITH ORANGES
  - ASSUMPTIONS OR JUDGMENTS ARE MADE
  - CAVEATS AND QUALIFIERS ARE FORGOTTEN
- UNCERTAINTY ABOUNDS!

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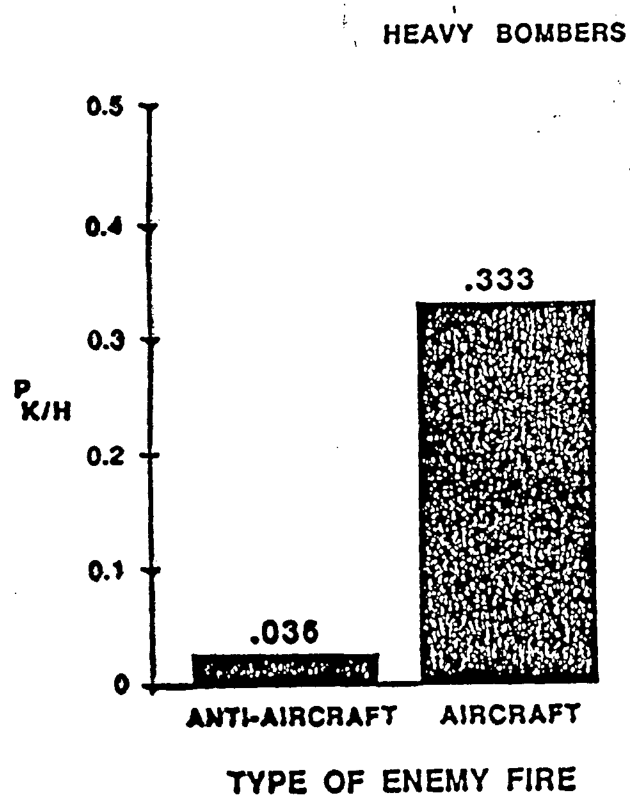
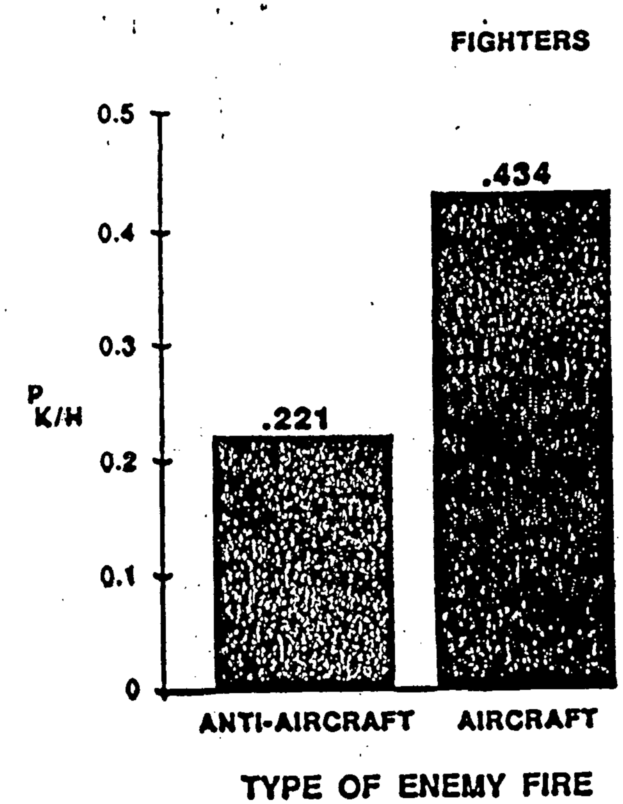
WORLD WAR II

OVERVIEW

WORLD WAR II AIRCRAFT VULNERABILITY (PK/H) DATA (U)

DATA FROM ALL THEATERS





*B-17, B-24, PB4Y

NOTE - $P_{K/H}$ EQUALS # AIRCRAFT LOST/ # AIRCRAFT HIT

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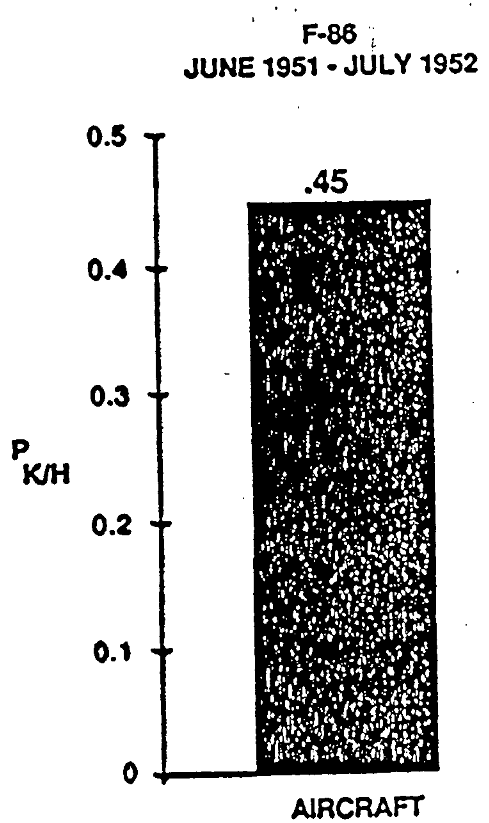
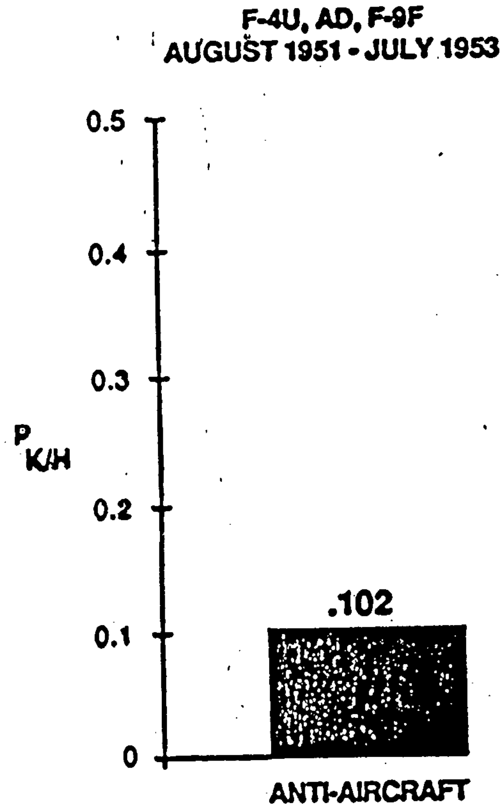
KOREAN WAR

OVERVIEW

KOREAN WAR AIRCRAFT VULNERABILITY (PK/H) DATA (U)





TYPE OF THREAT

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SOUTHEAST ASIA

OVERVIEW

AIRCRAFT LOST

	HOSTILE ACTION IN AIR	ALL HOSTILE ACTION	TOTAL (WITH OPERATIONAL)
FIXED WING	2420	2561	3720
HELICOPTER	2382	2587	4869
TOTAL	4801	5148	8589

OVER 30,000 RECORDED COMBAT DAMAGE INCIDENTS

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BY COUNTRY

	FIXED WING	HELICOPTER
CAMBODIA	36	123
LAOS	478	70
NORTH VIETNAM	1096	12
SOUTH VIETNAM	944	2381
THAILAND	3	1
OTHER	4	0
	2561	2587

BY SERVICE

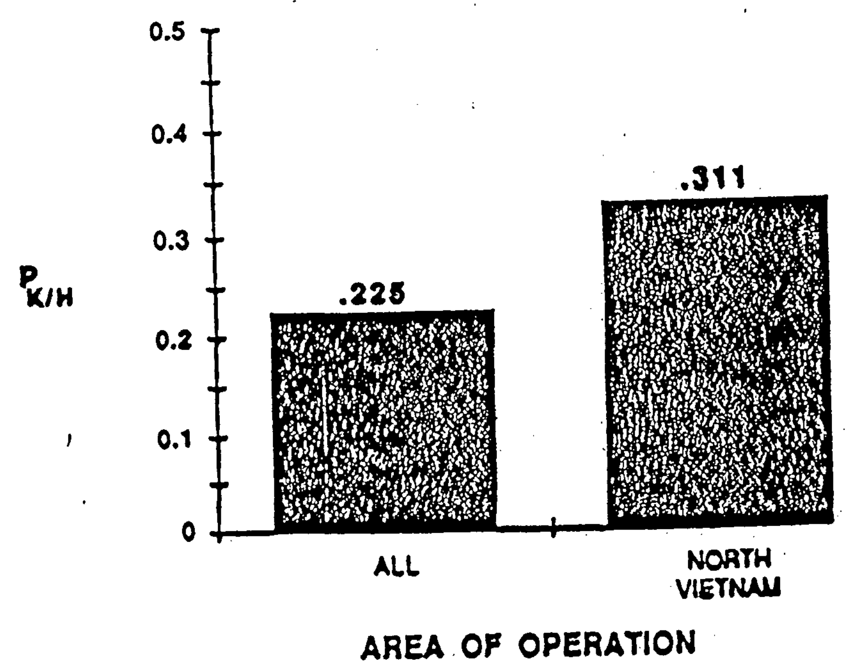
US MILITARY AIRCRAFT LOSSES IN SOUTHEAST ASIA (HOSTILE ACTION ONLY)

SERVICE	FIXED WING	ROTARY WING	TOTAL
USAF	1679	58	1737
USN	531	13	544
USMC	194	270	464
USA	157	2246	2403
TOTAL	2561	2587	5148

SOUTHEAST ASIA VULNERABILITY (PK/H) DATA (U)

ALL U.S. FIXED-WING AIRCRAFT, ATTACK SORTIES

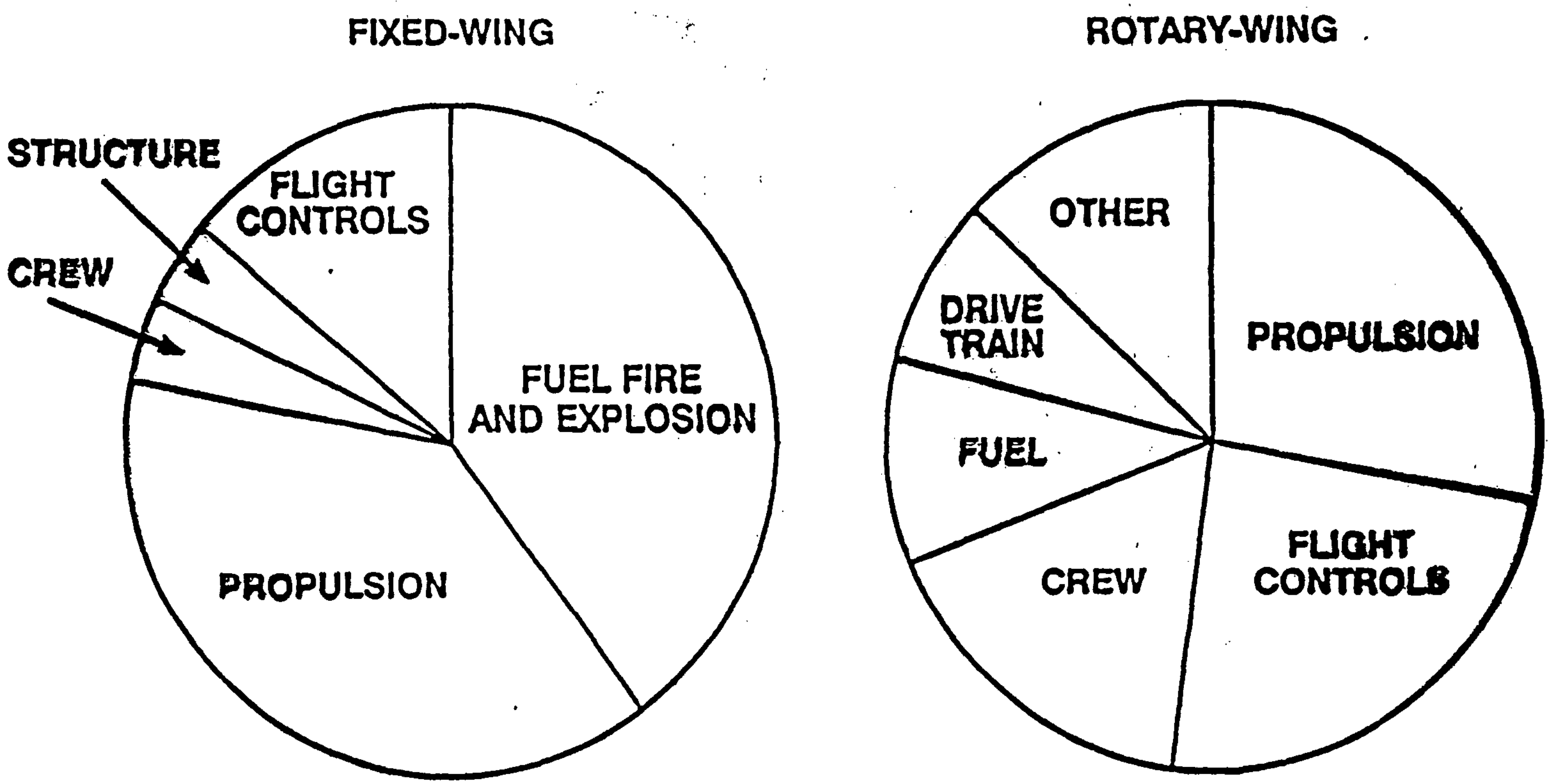
CY 1996 - CY 1973



NOTE - NUMBER MAY BE HIGH; NUMBER OF DOCUMENTED DAMAGE INCIDENTS MAY BE LOW

OVERVIEW

CONTRIBUTORS TO VULNERABILITY SOUTHEAST ASIA DATA



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FALKLANDS

1982

OVERVIEW

FALKLANDS - BRITISH HARRIER LOSSES (U)

TYPE AIRCRAFT	THREAT
SEA HARRIER	AAA
RAF HARRIER	BLOWPIPE
RAF HARRIER	AAA
RAF HARRIER	AAA
SEA HARRIER	ROLAND

TOTAL - 5

NOTE - DATA SYNTHESIZED FROM OPEN SOURCES

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OVERVIEW

FALKLANDS - BRITISH HELICOPTER LOSSES (U)

TYPE AIRCRAFT	NUMBER LOST
SEA KING	2
COMMANDOS	3
WESSEX	10-12
SCOUT	1
GAZELLE	SEVERAL
LYNX	SEVERAL

NOTE - DATA SYNTHESIZED FROM OPEN SOURCES

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OVERVIEW

FALKLANDS - ARGENTINA AIRCRAFT LOSSES (U)

TYPE AIRCRAFT	NUMBER LOST
SKYHAWK	31
MIRAGE	26
PUCARA	23
HELICOPTERS	18
OTHER	11
TOTAL:	109

NOTE - BRITISH CLAIMS SYNTHESIZED FROM OPEN SOURCES

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GRENADA
OCTOBER 1983

GRENADA SCOREBOARD (U)

THREAT - 7.62 MM, 12.7 MM, 14.5 MM, 23 MM

TYPE AIRCRAFT	NUMBER LOST	NUMBER DAMAGED
AH-1T	2	?
CH-46E	1	?
UH-69A	4 (?)	5
TOTAL:	7	11

Pk/h = .38

NOTE - DATA ARE FROM OPEN SOURCES

LIBYA

APRIL 1986

OVERVIEW

LIBYA SCOREBOARD (U)

TYPE AIRCRAFT	NUMBER ENGAGED	NUMBER LOST
F-111F	13	1
A-6E	14	0
F/A-18	6	0
A-7E	6	0
TOTAL:	39	1

NOTE - APPROXIMATELY 25 AIRCRAFT ATTACKED THE TARGETS

DATA SYNTHESIZED FROM OPEN SOURCES

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DESERT STORM

1991

OVERVIEW

ANALYSIS

TOTAL SORTIES -- 93228*

HIT RATE / 1000 = .68

LOSS RATE / 1000 = .3

PROBABILITY OF KILL/HIT = .41

* EXCLUDING ARMY SORTIES, HITS, AND LOSSES

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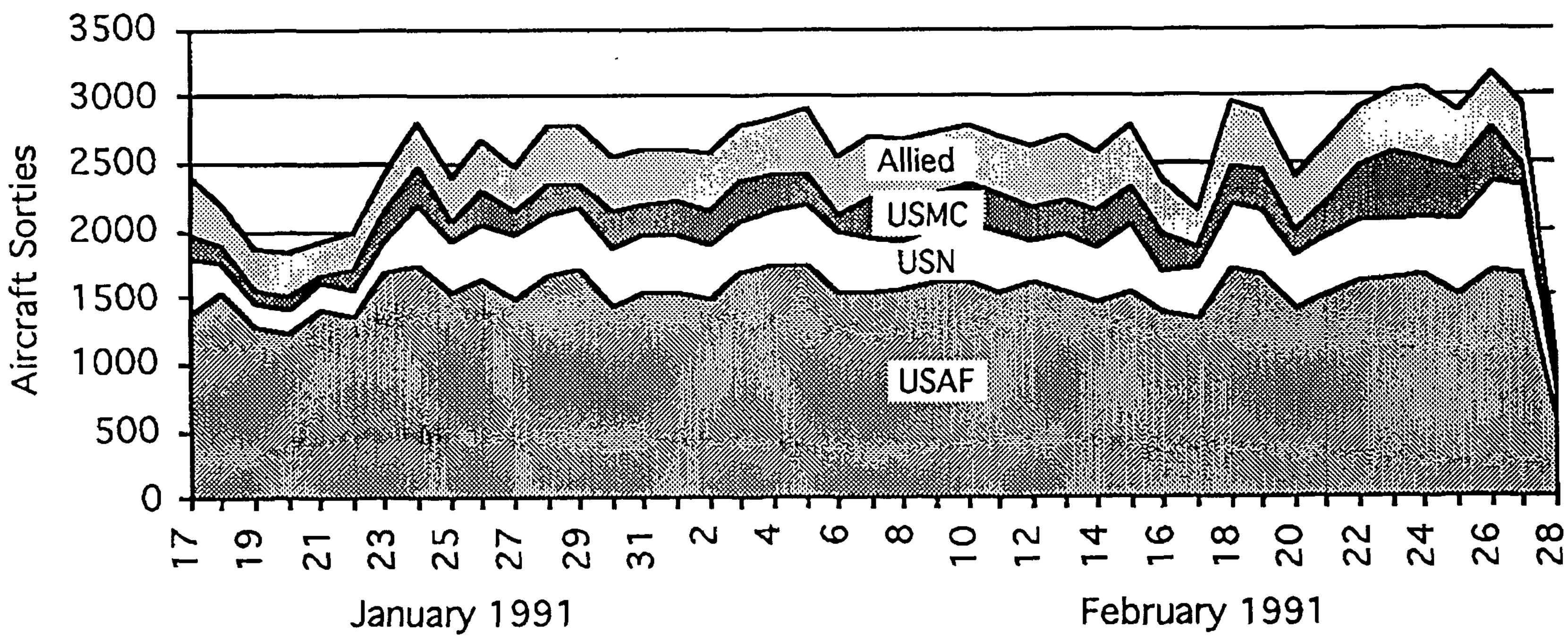
MISSION/CAMPAIGN

DESERT STORM SORTIES



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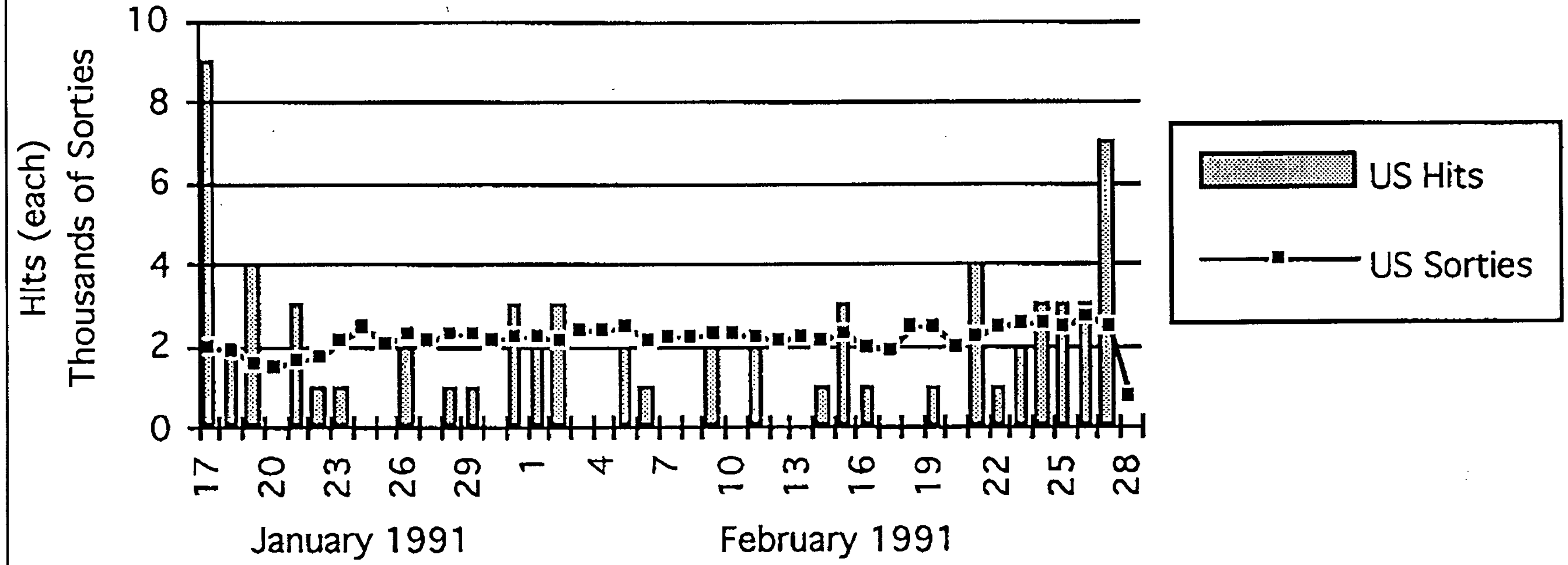
MISSION/CAMPAIGN

DESERT STORM DAILY SORTIES & HITS



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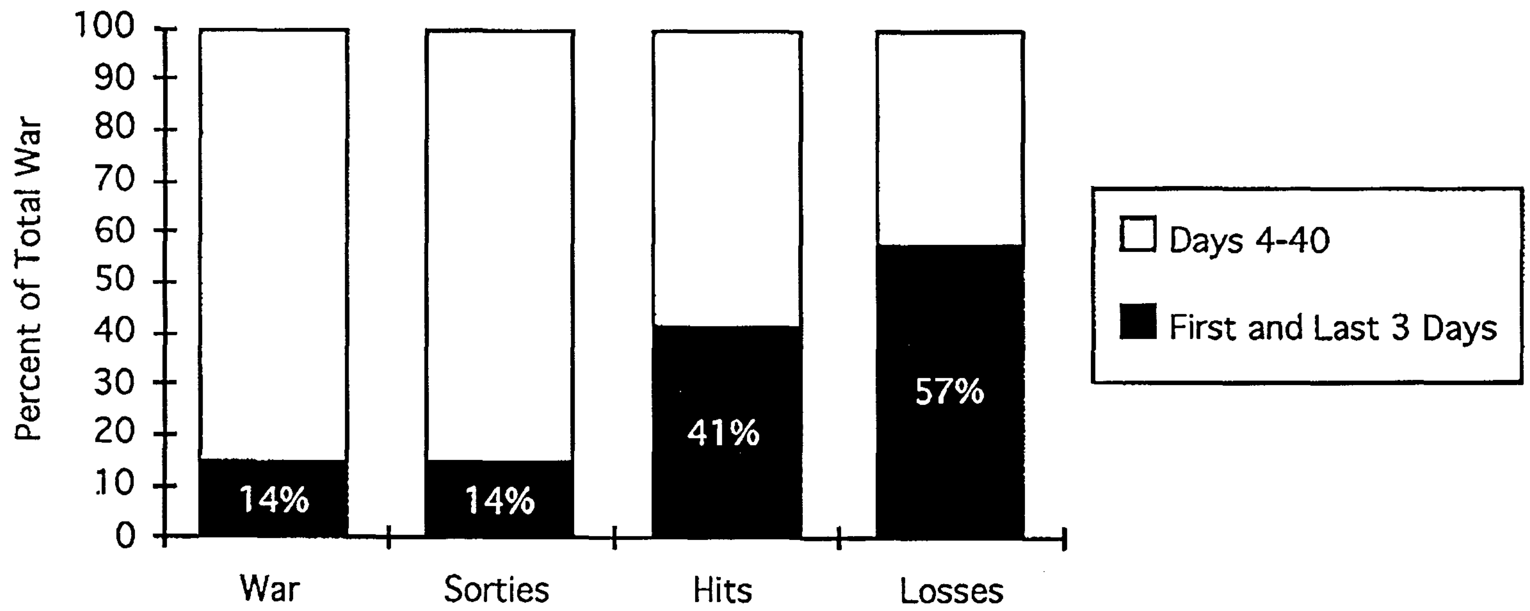
MISSION/CAMPAIGN

DESERT STORM START/END DAYS



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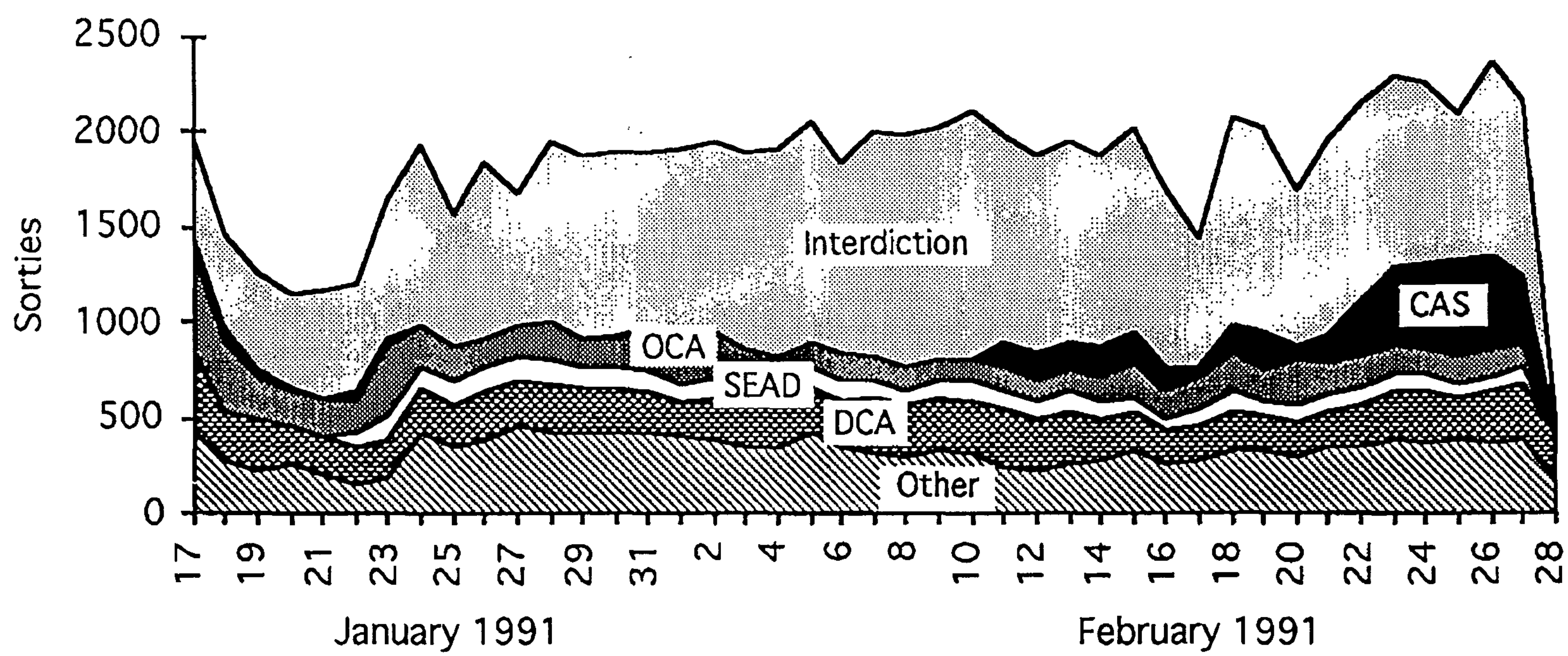
MISSION/CAMPAIGN

DESERT STORM SORTIES BY MISSION



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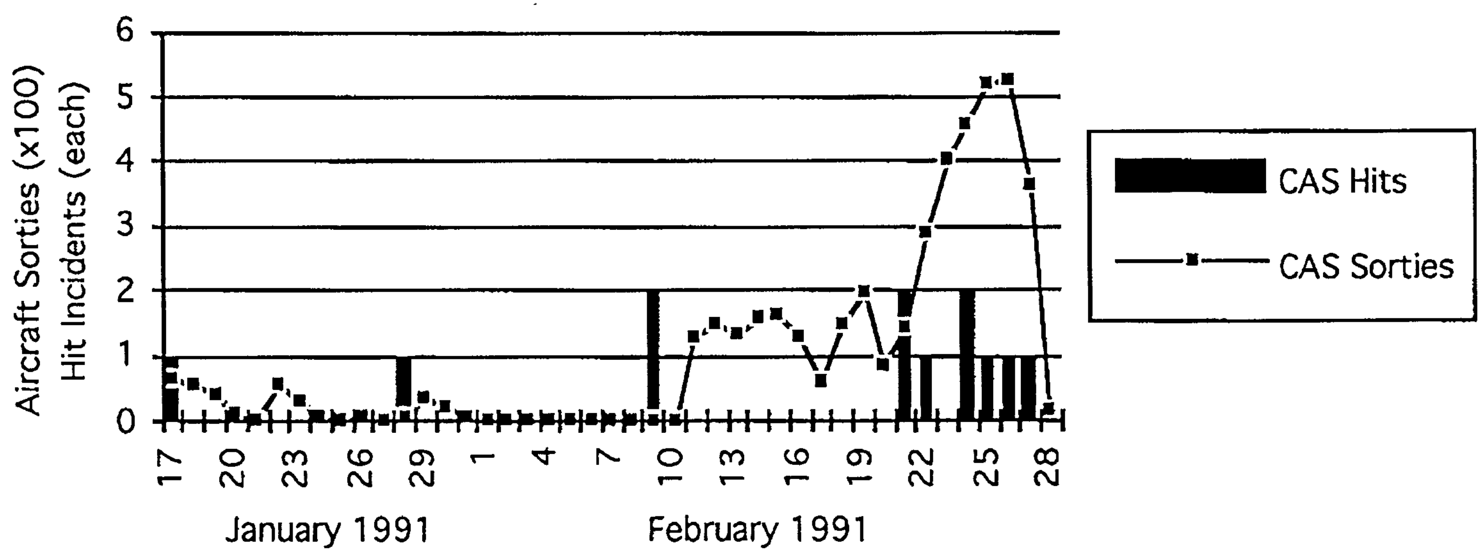
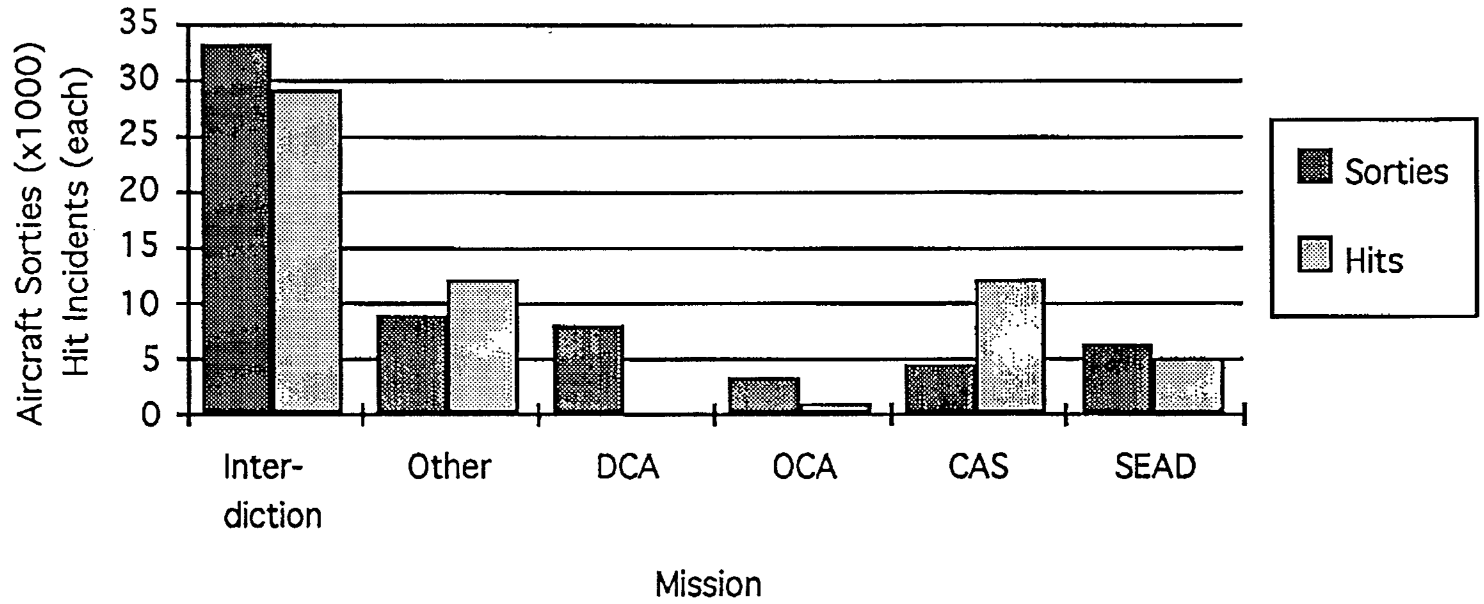
DESERT STORM CAS



MISSION/CAMPAIGN

DESERT STORM HITS BY MISSION



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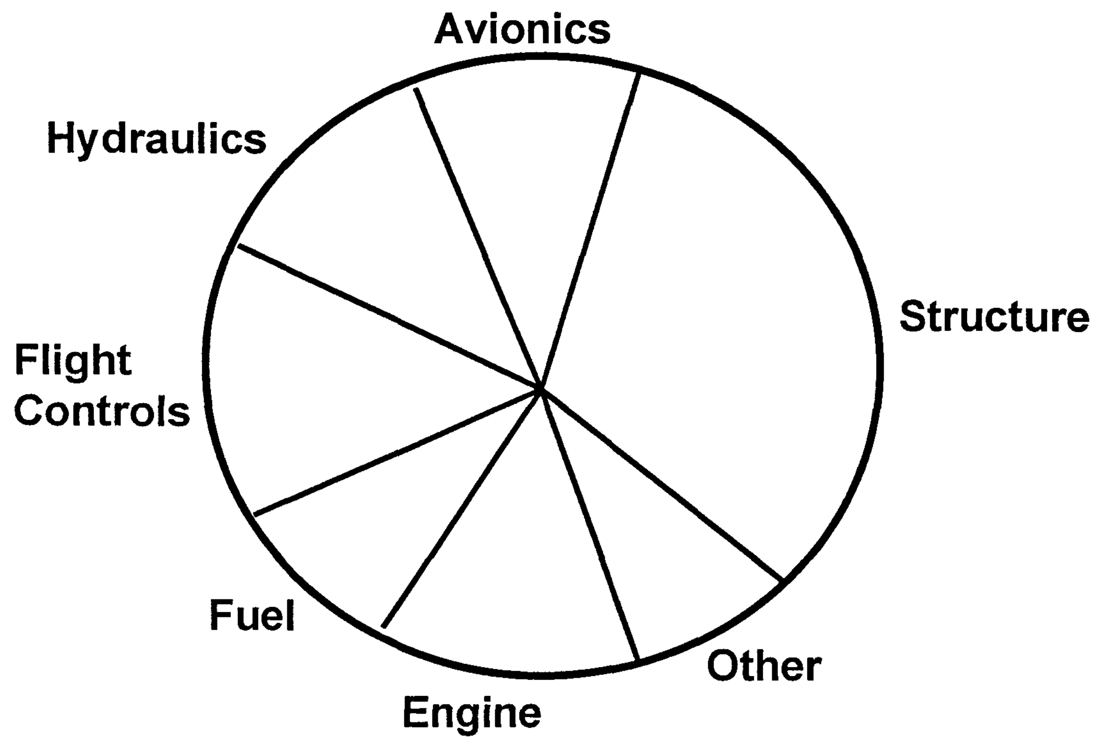
SUBSYSTEM DAMAGE



NOTE: DOES NOT INCLUDE 20 AIRCRAFT WITH UNKNOWN SUBSYSTEM DAMAGE

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OBSERVATION

PROBABILITY OF KILL GIVEN A HIT HAS BEEN RELATIVELY CONSTANT FOR LAST 60 YEARS

THE QUESTION - DOES THIS MEAN THAT THE VULNERABILITY REDUCTION COMMUNITY HAS FAILED?

THE ANSWER - NO, THE THREAT HAS EVOLVED

- SEA PRIMARILY SA/AAA
- DESERT STORM MORE PF SAMS & IR SAMS

THE CHALLENGE - TO CONTINUE TO KEEP PACE WITH INCREASING LETHALITY OF THE THREAT.

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SUMMARY

LOSSES AND DAMAGE MUCH LESS THAN EXPECTED

- SUSCEPTIBILITY LOWER
- THREAT CAPABILITY/TRAINING LOWER
- TACTICS - SURPRIZE, SEAD, TARGET SELECTION

MISCELLANEOUS OBSERVATIONS

- SOME MISSIONS INHERENTLY MORE DANGEROUS
- SOME DATA QUIRKS INTERDICTION VS SEAD
- PROBABILITY OF KILL GIVEN HIT AS EXPECTED
- AIR POWER CRUCIAL TO DECISIVE, SUCCESSFUL, LOW LOSS CAMPAIGN

COMBAT DATA USES IN ANALYSIS

- **To Provide Guidance on Encounter Conditions/Threats**
- **To Substantiate Flight Critical Subsystems & Responses**
- **To Provide Data to Support Analysis Inputs/Compare to Outputs**
- **To Substantiate Single Hit Analysis Vs. Multiple Hit Analysis**
- **To Support Definition of Possible Test**
  - Identify Data Voids & Uncertainties
  - Assist in Realistic Test Design
- **Enhance Survivability**

SURVIAC

A History of the Survivability Design of Military Aircraft

Robert E. Ball[1]
Naval Postgraduate School
Monterey, California

Dale B. Atkinson[2]
Springfield, Virginia

Abstract

In simple words, survivability in combat is achieved by not getting hit by the enemy's weapons or withstanding the effects of any hits suffered. The likelihood an aircraft gets hit while on a mission is referred to as the aircraft's susceptibility, and the likelihood the aircraft is killed by the hit is referred to as the aircraft's vulnerability. Reduction of aircraft susceptibility is achieved by (1) the selection of the appropriate weapons, tactics, threat suppression, and support jamming for the mission, (2) reducing the aircraft's signatures, and (3) incorporating on-board threat warning equipment and countermeasures in the form of electromagnetic jammers and expendables. Reduction of aircraft vulnerability is achieved by (1) the use of redundant flight critical components, adequately separated so that a single hit does not kill them all, (2) properly locating the critical components to reduce vulnerability, (3) designing the critical components, or adding equipment, to suppress the effects of any hits, and (4) shielding those components that cannot be protected otherwise. All of these concepts for enhancing survivability impact the design of the aircraft. The importance of survivability in the design of aircraft has varied throughout the 20th century from a total neglect to the highest priority. This paper presents the evolution of the survivability design of aircraft from the beginning of World War II to the present time.

Introduction

Aircraft combat survivability is defined in [1] as "the capability of an aircraft to avoid and/or withstand a man-made hostile environment." The inability of an aircraft to avoid the radars, guns, ballistic projectiles, guided missiles, exploding warheads, and other elements that make up the hostile air defense environment is referred to as the susceptibility of the aircraft. An aircraft's susceptibility can be measured by the probability the aircraft is hit while on its mission, P_H. Thus, slow, low-flying aircraft that are easily detected, tracked, engaged and eventually hit with one or more damage-causing mechanisms associated with the enemy's weapons are very susceptible. Fast, high-flying aircraft that are difficult to detect, difficult to track if detected, difficult to engage if tracked, and difficult to hit if engaged are relatively unsusceptible.

The inability of an aircraft to withstand any hits by the hostile environment is referred to as the vulnerability of the aircraft. An aircraft's vulnerability can be measured by the conditional probability the aircraft is killed given a hit, $P_{K/H}$. Aircraft that have one engine, no fuel system fire/explosion protection, redundant but collocated hydraulic systems with flammable hydraulic fluid, and one unprotected pilot are very vulnerable. Aircraft with two widely separated engines, protected fuel systems, redundant and separated hydraulic systems with non-flammable hydraulic fluid, and shielding around the pilot are relatively invulnerable.

The survivability of an aircraft can be measured by the probability of survival, P_S, which depends upon the aircraft's susceptibility and vulnerability according to the equation

$$P_S = 1 - P_H P_{K/H}$$

Thus, survivability is enhanced when susceptibility and vulnerability are reduced.

[1] Distinguished Professor of Aeronautics and Astronautics, Fellow AIAA

[2] Consultant, Associate Fellow AIAA

Another aspect of survivability is the ability to rapidly repair any damage sustained in battle. If this damage cannot be quickly repaired, the aircraft may not be returned to action in time to contribute to the final outcome; and in essence it becomes a 'killed' aircraft. Thus, the design of an aircraft to allow the rapid repair of battle damage is an indirect contributor to survivability, not because it increases the survivability of the individual aircraft, but because it enhances force reconstitution and, consequently, force survivability.

Survivability Enhancement Features and Concepts

Any particular characteristic of the aircraft, specific piece of equipment, design technique, armament, or tactic that reduces either the susceptibility or the vulnerability of the aircraft has the potential for increasing survivability and is referred to as a survivability enhancement feature. [1] Table 1 contains a list of some of the survivability enhancement features that have been used on aircraft. Each of the survivability enhancement features listed in Table 1 can be grouped under one of the six concepts for reducing susceptibility or six concepts for reducing vulnerability. Table 2 contains the twelve survivability enhancements concepts with an example of a particular survivability enhancement feature under each concept.

Survivability and Aircraft Design

Combat survivability as a formal design discipline for aircraft is a relatively new concept. Although many aircraft of the past were designed with survivability in mind, particularly during WW II, until recently there was no "systems approach" to the survivability design solution. Guns and missiles were added for self-defense, fuel systems were protected from fire and explosions, better tactics were developed, electronic countermeasures (ECM) were used, more realistic training was provided, structures were made more resistant to enemy fire, and camouflage paint schemes were applied. However, all of this was done within the context of the individual aircraft design disciplines, and no attempt was made to justify the inclusion of any of these survivability enhancement features in the design other than to note that aircraft that had them lived longer in combat were "better" or more effective than those that didn't. The hard lessons learned in combat were fed back into the design of new and improved versions.

There were two reasons for this historical lack of a systems approach to survivability and a quantification of the "payoffs" or increase in operational effectiveness and the costs associated with a more survivable design. First, the systems approach to aircraft design had not been fully developed. Second, there were no specific design requirements imposed by the military Services on the various measures of survivability, such as the maximum allowable $P_{K/H}$ or vulnerable area (that area on the aircraft which if hit would cause an aircraft kill) or radar cross section, because survivability was not considered to be a formal attribute of a military aircraft. Consequently, there was no apparent need for a formal discipline.

The importance of survivability in the design of military aircraft increased dramatically in the middle 1960's when many aircraft, not specifically designed to be survivable, were shot down in Southeast Asia (SEA). In the years from 1963 to 1973, the U. S. military Services lost approximately 5,000 aircraft to enemy fire in SEA. The losses were nearly equally divided between fixed-wing aircraft and helicopters. Perhaps the first publication to bring attention to the technology that could make aircraft more survivable was the paper "Design of Fighter Aircraft for Combat Survivability," published in 1969. [2]

Because of the U.S. military's experience over the past five decades with aircraft that were not specifically designed to survive in combat, survivability has become a "critical system characteristic" that has emerged as a distinct and important design discipline. A viable, cost-effective technology exists for reducing susceptibility and vulnerability, a methodology exists for assessing survivability, education in survivability is available, testing for survivability is mandated, top level survivability design guidance is prescribed, and quantified requirements on the susceptibility and vulnerability of aircraft are now routinely specified. Table 3 shows the history of the requirements for survivability since 1950. Much of the credit for the increased emphasis on the survivability of aircraft goes to the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), which was established in 1971 with a goal to develop survivability as a design discipline. Credit also goes to the Department of Defense survivability organizations, the survivability engineers in the aircraft industry, and those military program managers that made sure their aircraft were designed to be survivable.

This paper will review the evolution of the survivability design of aircraft from the beginning of

World War II to the present time. The review will examine both susceptibility and vulnerability reduction. However, because of the classified nature of much of the technology for susceptibility reduction, the paper will emphasize vulnerability reduction.

Susceptibility Reduction

World War II

Susceptibility reduction has been a goal of the tactician from the beginning. The tactics, weapons selection, mission planning systems, force packaging, and threat suppression used by the military balance the requirement to accomplish the mission with the expected aircraft losses. This is known as managing attrition. Managing attrition by avoiding the enemy's air defense has always been a high priority goal. During WW II, hundreds of B–17s flew at high altitude in box formations, escorted by P–47 and P–51 fighters looking for the enemy fighters. The bombers were located far enough apart – so that an exploding shell from an anti-aircraft artillery piece (AAA), known as flak, would not damage or kill more than one aircraft – but close enough together so that the enemy fighters could not easily maneuver between them. They were loaded down with twin–50 cal machine guns mounted in electrically driven turrets, and eight of the ten crew members were firing guns at the enemy fighters. The weight of the guns and ammunition was approximately twice the weight of the bombs carried. [3] The B–17s flew during the day, which made them more susceptible, because they used the Norden bombsight which required the bombardier to see the target. The British flew their Lancaster and Halifax bombers at night because they had a better chance of avoiding the fighters and the flak. As a result, they were less susceptible and hence more survivable at night. However, it also was more difficult to destroy a particular factory or bridge when bombing at night. The development of electronic countermeasures to the early radar systems was a high priority item, and radar–reflecting chaff or "window" was used extensively, after some early hesitation because of the fear the enemy might use it against the allied radars. References [4] and [5] present a detailed history of the use of electronic countermeasures in WW II.

The Southeast Asia Conflict

Many of the tactics used to avoid the hostile environment in SEA in the decade from 1963–72 were essentially the same as those used in WW II, such as formations of bombers escorted by fighters. However, the bombers, such as the B–52, F–105, F–4, A–4, A–6, and A–7, had little or no self–defense capability. They relied totally on the fighter escorts, such as the F–4, to keep the enemy fighters away. The surface–to–air guided missile (SAM) emerged as a major threat to contend with, and on–board threat warning receivers and electronic jamming equipment, and the support jamming provided by aircraft such as the EA–6, became major contributors to survivability. Specially modified aircraft were used in the suppression of enemy air defense (SEAD) role to seek out and destroy the enemy SAM launch sites. Mission profiles were often used that kept the aircraft out of the high altitude envelopes of the SAMs but put them within range of ground–based small arms and AAA fire. Reference [5] presents a brief history of the use of electronic warfare in the SEA conflict.

The Recent Past

As a result of the large number of tactical and strategic aircraft lost in the SEA conflict, a major revolution in the design priorities of military aircraft began in the late 1970's when the first stealth aircraft programs were started in an attempt to reduce aircraft susceptibility without the use of large numbers of supporting aircraft. These so-called stealthy aircraft, such as the F–117, A–12, F–22, RAH–66, and the B–2, look different. Their engine inlets and exhausts are modified, their wing sweep angles are high, some of them lack the traditional vertical tail, and they do not have the many bumps and bulges that non–stealthy aircraft have. Even the relatively small stealth aircraft carry their ordnance inside.

There are many other changes associated with susceptibility reduction that are not so obvious. Because of the stealthy design, the flight control system may have to contend with statically unstable aircraft. Manufacturing procedures must contend with different materials, higher tolerances, and complex shaping requirements; and the sensors must be properly located on the aircraft to minimize their contribution to the aircraft's signatures while maintaining their ability to sense.

Some other not–so–obvious design impacts are related to the requirements associated with the electronic warfare equipment carried by the aircraft. This equipment provides the concepts of threat warning, noise jamming and deceiving, and expendables. Adequate space, cooling, and electrical power for the

processors, sensors, and data buses put additional requirements on the design. Should the countermeasures packages be carried externally or internally. Where are the antennas located? Will they affect the radar signature? Another not-so-obvious impact of susceptibility reduction, but one that can be a major contributor to aircraft weight, is the mission flight profile. Aircraft are designed to fly a particular flight profile, such as high–low–low–high. With this profile, the aircraft takes off, climbs to high altitude, and efficiently cruises toward the target. It then drops down to a low altitude to avoid detection by the enemy's air defense sensors and high altitude SAMs and jinks to avoid being hit by enemy gunfire. The target is attacked at low altitude, typically with a pop–up maneuver to acquire the target. After attacking the target, the aircraft heads for home, first at a low altitude until out of the enemy's weapon envelopes, and then at a high altitude for optimum cruise efficiency. The drop down to low altitude, which is solely for enhanced survivability, puts the aircraft in a much more severe flight environment. Drag increases significantly, fuel is burned at a much higher rate to maintain the fast speed required to survive the transit through the enemy territory, and the air loads on the aircraft are much higher than those at high altitude with no maneuvering. One of the most attractive features of a stealthy aircraft is the potential use of a high–high–high flight profile; it keeps the aircraft out of the range of the ground–based guns, a long–time, lethal foe of aircraft.

Vulnerability Reduction

Some General Principles

The vulnerability of an aircraft is reduced by designing the aircraft to withstand any hits by the damage–causing mechanisms created by the enemy warheads, such as penetrators, fragments, incendiary particles, and blast. This is acomplished by ensuring that the critical components on the aircraft continue to function after the aircraft is hit. Critical components are those components whose loss of function or whose kill mode leads to the loss of an essential function, such as lift, thrust, and control for flight. The kill modes associated with the components of each of the major systems on an aircraft are listed in Table 4. Vulnerability is reduced by preventing these kill modes from occurring.

World War II

The vulnerability reduction features used on the aircraft of WW II were the result of wartime experience. Most of the aircraft that were in use at the beginning of the war, such as the Fairey Battle, Brewster Buffalo, Grumman F4F Wildcat, and Boeing B–17, were either extensively modified during the war to make them more survivable or were used on missions with low threat levels. An excellent paper on the effects of enemy gun fire on the German Ju–88 notes that the cost of the Ju–88s lost in combat was the largest single expenditure of the entire program. [6] According to [6], the operations of the Ju–88 were discontinued in 1944 because the opposition of the Allies' standard pursuit aircraft had become so strong. References [1], [3], and [7] present many of the vulnerability features used on several aircraft of the WW II. Table ˉ lists some of these features. Each feature was incorporated to prevent one or more of the kill modes listed in Table 4 from occurring.

The Southeast Asia Conflict

Many of the aircraft that fought in the Southeast Asia conflict were designed for high altitude fighting with missiles and for nuclear war. For example, the McDonnell F–4 Phantom II was originally designed as a deck–launched interceptor for the U.S. Navy that would dash out to the enemy bombers approaching the carrier and kill them with air–to–air missiles. There was no (or very little) attention paid during the design of the F–4 (or to the design of any other aircraft of that era) to the damage that enemy guns or guided missiles might do to the aircraft. Due to this lack of attention to survivability during design, the U.S. military began to lose a significant number of aircraft as the SEA conflict intensified.

Because of these losses, the Air Force sent a fact–finding team into the area in 1966 to determine the loss cause(s). The team interviewed crew members who had been shot down and recovered and the wingmen of those not recovered. They also inspected and collected data on battle–damaged aircraft that had returned to base. The battle damage data was used to determine the location and types of damage that did not result in an aircraft loss. The original Air Force directive that identified the problem conjectured that the aircraft were falling out of the sky because of damage to the structure. However, the on–site team determined that the single most important cause of aircraft losses was actually fuel system fire or explosion. Another significant cause of aircraft losses was damage to the flight control system.

Often, damage to the redundant (but collocated) hydraulic components would result in hard–over control surface failures and an uncontrollable aircraft, forcing the pilot to eject – if he could. Many of the control failures were caused by a fuel or hydraulic fluid fire that destroyed the control components.

After the first Air Force team returned in 1966, they recommended a number of actions to reduce the future loss of aircraft. All were approved by Air Force Headquarters. One recommendation was to conduct vulnerability assessments on the tactical aircraft operating in North Vietanm (the F–4, RF–4, F–105, and RF–101) and to develop vulnerability reduction retrofit–packages based upon the combat data collected and the vulnerability assessments. The primary emphasis was on the suppression of fuel system fire and explosion and the prevention of the loss of flight control. Self–sealing fuel tanks and lines and the placement of flexible, reticulated polyurethane orange foam into the fuel tanks were some of the vulnerability reduction features designed to prevent fuel–related fires and explosions.

Features designed to prevent the loss of control were added to both the F–105 and the F–4. A stabilator lock that was activated by the pilot if all hydraulic power was lost at the stabilator actuator was added to the F–105. On the F–4, an Auxillary Power Unit (APU) was added to the stabilator actuator, and armor was placed below the hydraulic components. Another change to the flight control system of the F–4 concerned the hydraulic power supplied to the aluminum aileron actuators. The original hydraulic system consisted of two primary flight control systems, PC1 and PC2, and the utility system. Both PC1 and PC2 supplied power to both aileron actuators. Thus, a hit near either of the aileron actuators (or a fatigue crack) could damage the aluminum actuator, causing the loss of both PC1 and PC2, and the subsequent loss of the aircraft. In the more survivable design, the aluminum actuators were replaced with steel actuators, and the hydraulic lines were replumbed, with utility replacing PC1 in one wing and PC2 in the other wing. With this less vulnerable design, a hit near the aileron actuator could cause a loss of PC1 and utility, or PC2 and utility, but not both PC1 and PC2. [8]

This vulnerability reduction design of the aileron hydraulic system saved the lives of at least 24 air crews that were flying the modified F–4 when they lost all hydraulics in one wing. Twelve of those aircraft were in a combat zone. The resulting savings due to this particular feature were estimated to be $51M (at $2.5M per aircraft) plus the lives of the 24 air crews. The cost of the modification was $9M, but it would have been much less had the hydraulic separation been in the original design. [8] There are many other examples of aircraft modifications that were made to reduce vulnerabilities that were discovered in combat. Table 6 lists some of the features incorporated on the aircraft that fought in SEA. These features were added to prevent one or more of the kill modes listed in Table 4. Many of them, if not most, were retrofitted, and many also contributed to aircraft safety.

The Recent Past

Many of the aircraft flying today were designed during and after the SEA conflict. The lessons learned in combat in that conflict have strongly influenced the design of these aircraft. Three of these aircraft, the Air Force's A–10A Thunderbolt II (affectionately known as the Warthog), the Navy's F/A–18A Hornet, and the Army's UH–60A Blackhawk, have been selected as examples to illustrate the technology for reducing vulnerability that evolved from the late 1960's through the middle 1980's.

The A–10's primary mission was to kill tanks with a 30mm gun and air–to–surface missiles. In this role, it would face a variety of guns and missiles, and it's vulnerability would be tested in combat. Consequently, the aircraft was the first modern fixed–wing aircraft to be designed, from its inception, to a complete set of survivability requirements. It incorporates over 100 vulnerability reduction features, many of which were verified by ballistic testing. In Operation Desert Storm in 1991, the A–10 had an opportunity to show what it could do. According to Air Force Capt. Paul Johnson, who flew home from a mission over Kuwait with a gaping hole in his A–10's right wing, "We always expected the A–10 to be a tough customer, but it hadn't been proven." [9] The survivability and battle damage repair features that were designed into the A–10 'paid off' in Desert Storm. According to an article in Aviation Week & Space Technology, "Survivability features designed into the Fairchild A–10 proved their worth during its first exposure to combat in Operation Desert Storm, when many Thunderbolts flew home despite extensive battle damage sustained in successful low–level attacks on enemy tanks and artillery. ... Most of the damaged aircraft were returned quickly to service by U.S. Air Force aircraft battle damage repair (ABDR) crews. ... Of 20 aircraft that were at least 'significantly' damaged, only one could not be returned to service by ABDR crews ... ." [10] According to Capt. Johnson,

"The guys developed a great affection for the airplane and a very healthy respect for what it could absorb." [9]

The F/A–18 was the Navy's first aircraft in which survivability considerations played a major role in the design. Trade–off studies were performed to determine the payoffs and costs associated with each enhancement feature considered. Those features that had high pay–offs with relatively low costs were incorporated because the Hornet is both a fighter and an attack aircraft and had to perform well in both roles. The F/A–18 is the Navy's most survivable aircraft flying today. It, too, proved itself to be a survivable aircraft in Desert Storm.

Because of the large number of Army helicopters lost to small arms fire in SEA, the UH–60, which was the winning design for the Utility Tactical Transport Aircraft System (UTTAS) competition, had a firm design requirement on vulnerability. The helicopter in forward flight was to be capable of safe flight for at least 30 minutes after a single hit by a 7.62mm API projectile. [11] In the vernacular of the vulnerability engineer, the helicopter must have zero vulnerable area for a B level attrition kill. A minimum vulnerable area to the 23mm HEI was a design goal. The reduced vulnerability paid off in Grenada. "The BLACKHAWK played a key role in combat during the 1983 Grenada invasion. ... It sustained and survived small arms and 23mm anti-aircraft fire while carrying out its mission of transporting and supporting Army Rangers. Of the 32 BLACKHAWKS used in Grenada, ten were damaged in combat. One helicopter had 45 bullet holes that damaged the rotor blades, fuel tanks, and control systems, yet it still managed to complete its mission." [12]

To illustrate the state–of–the–art of vulnerability reduction design in the recent past, the vulnerability reduction features used on the A–10A, F/A–18A, and the UH–60A to prevent the system kill modes from occurring are given in Tables 7a–e and Figs. 1–3 for the major systems. [13, 14, and 15] All three aircraft, as well as the F–117 and many of the other aircraft involved in the operation, proved themselves to be survivable aircraft in Desert Storm. They took some hits, but suffered very few losses. This combat experience validated the approach to survivability design that was taken during 1970's and 80's.

Testing for Survivability

The current generation of operational aircraft, as well as those in development, are undergoing extensive life fire testing. The Joint Live Fire (JLF) test program, initiated in the early 1980's, has tested the F–15, F–16, F/A–18, AV–8B, UH–60A, and AH–64A to both non–explosive and explosive ballistic projectiles. The congressionally mandated Live Fire Test (LFT) law for aircraft in development, passed in FY87, requires realistic vulnerability tests on the complete aircraft, with all combustibles on–board, using weapons likely to be encountered in combat. If such tests are unreasonably expensive and impractical, a waiver must be approved by the Secretary of Defense prior to the entry into Engineering and Manufacturing Development, and an alternate realistic test program plan must be submitted and approved. Vulnerability testing of components and subsystems early in the development cycle is strongly encouraged in order to identify vulnerabilities and eliminate them without major weight and cost penalties. The law has had a major beneficial effect on the vulnerability reduction of many of the aircraft currently operational, as well as those in development, and this beneficial effect should continue into the future. [16]

Present and Future Designs for Survivability

The current generation of military tactical aircraft now in development or low rate initial production, e.g., the F–22, F/A–18E/F, V–22, and RAH–66, have strong survivability requirements. The C–17 is the first cargo aircraft with survivability requirements on the original design because its mission requires it to go in harm's way. Both susceptibility and vulnerability are being reduced using the technology that has evolved over the last thirty years. A balanced design between susceptibility and vulnerability issues is achieved using trade–off studies to determine the proper balance for the different aircraft with their different missions. This approach is expected to continue into the future, with an improved capability for conducting integrated survivability assessments and trade–off studies, including tactics, electronic warfare, and signature reduction, developed through the efforts of the JTCG/AS and others.

The designer of future aircraft will face different problems when trying to design survivable aircraft, but the fundamental approches to solving those problems remains the same: reduce susceptibility and reduce

vulnerability. One of the survivability issues on aircraft in design today, as well as those of the future, is the increased use of composite materials, which affect (1) an aircraft's signatures, and hence susceptibility, (2) its structural vulnerability, and (3) the ability to rapidly repair battle damage. Other issues are the possible reduction in the number of engines on an aircraft due to the increase in engine reliability, the trend toward an all or mostly electric aircraft, the significant increase in the reliance on avionics, with digital data buses transporting flight critical signals throughout the aircraft, and the mandated requirement to find a replacement for the current fire extinguishing/fuel tank inerting systems that use a environmentally destructive gas, such as Halon 1301.

Conclusions

Survivability has come a long way in the past thirty years. It is now a combat tested, critical system characteristic, with performance requirements, an enhancement technology, and an assessment methodology. The original goal of the JTCG/AS in 1971 to establish survivability as a design discipline has been achieved. This goal has been reached because the U.S. military Services have learned that aircraft that have not been designed to survive in combat are not effective in combat.

However, there are many changes that are either here now or are looming ahead that can impact the survivability of those aircraft that will be operating in the twenty-first century. The affordability of modern military aircraft has become a major issue, with the potential consequence of less survivable aircraft because of a reliance on relatively inexpensive, off-the-shelf, peacetime designs. The authors believe that when procuring affordable military aircraft, survivability must not 'drop through the crack' because of the elimination of the military specifications and standards that have become a controversial issue. Military aircraft must be designed to fight and survive in wartime, not just to fly in peacetime.

The Department of Defense (DoD) is downsizing, and the availability of people to pay attention to those details that are unique to combat may decline. The authors believe that as DoD downsizes, the resources, personnel, and facilities required for survivability assessment, design, and test and evaluation, must not be downsized below a critical mass. Providing support to program managers, developing new technology, and conducting realistic live fire and operational tests to evaluate susceptibility, vulnerability, and survivability requires an investment for the security of the nation.

Finally, the identification of the specific threats to future aircraft is difficult, at best, which may lead some people to the conclusion that there are no serious threats to contend with; and if there are no threats, survivability can be ignored. The authors believe that history has shown, and will continue to show, that there is always another threat waiting just around the corner. Having aircraft available that are both lethal and survivable will help to dissuade potential adversaries from any foolish action.

In conclusion, the authors believe that if the survivability community continues to work together in the future, as it has in the past, then survivability as a design discipline will continue to mature, and the U.S. military aircraft of the future will be more survivable and thus more effective.

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Table 1 Some Typical Survivability Enhancement Features

Speed and altitude	Maneuverability/agility	Chaff and flares
Fire/explosion protection	Terrain following	Hydraulic ram protection
Self–repairing flight controls	No fuel adjacent to air inlets	Rugged structure
Lethal stand–off weapons	Self–defense missiles and guns	Good target acquisition capability
Night–time capability	Crew situational awareness	Threat warning system
More than one engine – separated	Fighter escort	Mission planning system
Low signatures or observables	Crew skill and experience	Antiradiation weapons
Tactics	Nonflammable hydraulic fluid	Armor
On–board electronic countermeasures	Redundant and separated hydraulics	Stand–off electronic countermeasures

Table 2 The Twelve Survivability Enhancement Concepts [1]

Susceptibility Reduction	Vulnerability Reduction
Threat warning – missile approach warning receiver	Component redundancy (with separation) – two widely separated engines
Noise jamming and deceiving – ALQ–126B on–board ECM	Component location – no fuel adjacent to air inlets
Expendables – flares	Passive damage suppression – explosion suppression foam in fuel tank ullages
Signature reduction – shaping to reduce the radar signature	Active damage suppression – fire detection and extinguishing in engine bays
Threat suppression – anti–radiation missile	Component shielding –armored seats
Tactics, performance, & crew skill & experience – terrain following	Component elimination/replacement – nonflammable hydraulics

Table 4 A List of System Damage–Caused Failure (Kill) Modes [1]

Fuel	Propulsion	Flight Control
Fuel supply depletion	Fuel ingestion	Disruption of control signal path
In-tank fire/explosion	Foreign object ingestion	Loss of control power
Void space fire/explosion	Inlet flow distortion	Loss of aircraft motion data
Sustained exterior fire	Lubrication starvation	Damage to control surfaces and hinges
Hydraulic ram	Compressor case perforation or distortion	Hydraulic fluid fire
Power Train and Rotor Blade/Propeller	Combustor Case perforation	
Loss of lubrication	Turbine section failure	Structural
Mechanical/structural damage	Exhaust duct failure	Structure removal
	Engine controls and accessories failure	Pressure overload
		Thermal weakening
Electrical Power		Penetration
Severing or grounding	Crew	
Mechanical failure	Injury, incapacitation, or death	Avionics
Overheating		Penetrator/fragment damage
	Armament	Fire/explosion/overheat
	Fire/Explosion	

Table 3 New U.S. Military Aircraft Starts (Approximate Dates)

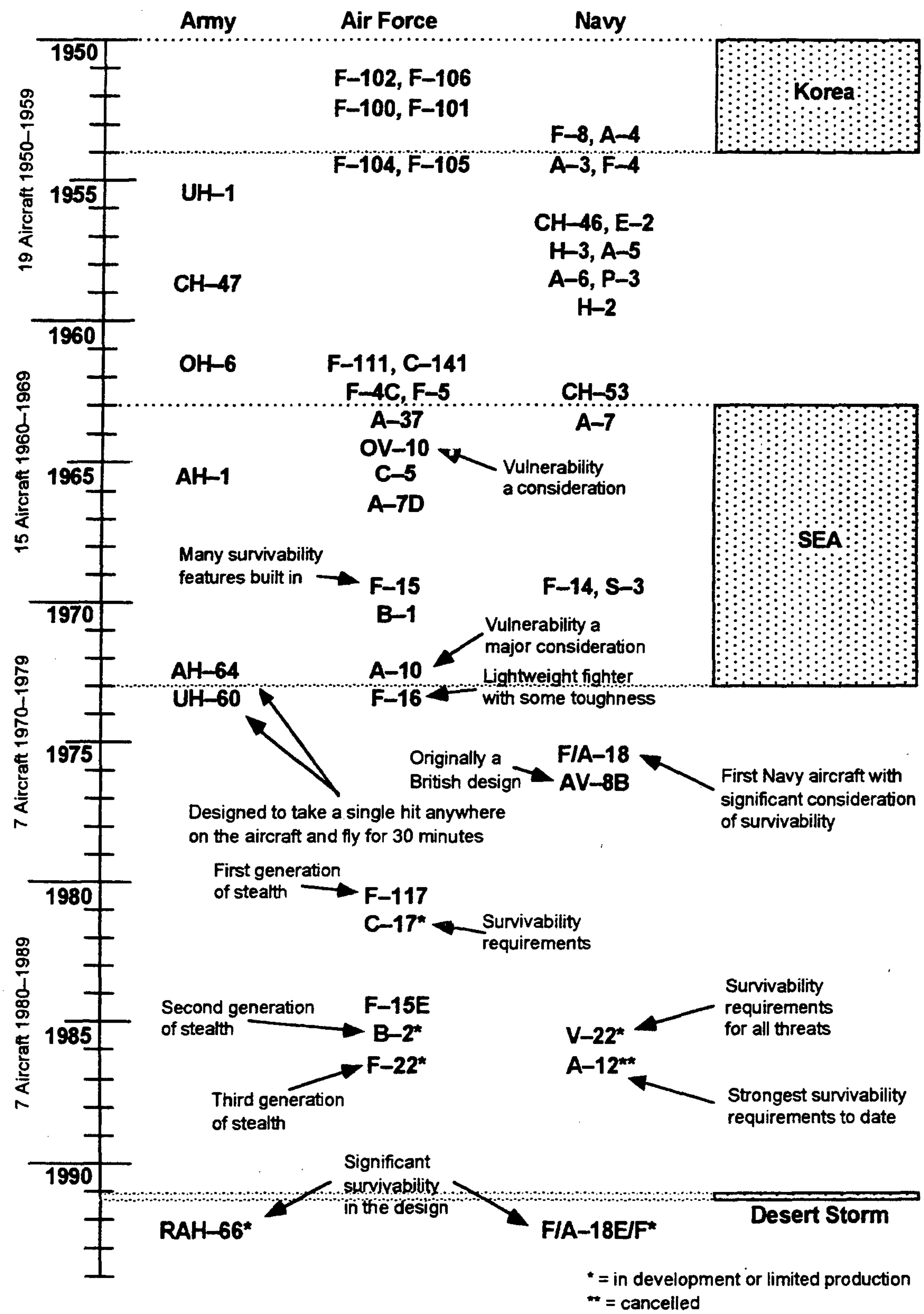

Table 5 Some Vulnerability Reduction Features used on WW II Aircraft

Armor plating	Self-sealing fuel tanks
Location of cooling and lubrication components	Fuel venting and void space filling
Bullet-proof glass canopy	Fuel tank ullage inerting
Rugged construction	Fuel tank depressurization
Air-cooled engines	Fire extinguishing (crew and engines)
Emergency extension of landing gear	Fuel tank cross-over lines with shut-off valves
Back-up propeller feathering subsystem	Firewalls

Table 6 Some Vulnerability Reduction Features used on SEA Aircraft

Orange foam in fuel tanks	Rerouted hydraulics in wings
Back-up flight controls and surfaces	Added APU
Stabilator lock	Independent, self-sealing fuel feed tanks and lines
Bomb bay fire extinguishers	Ram air emergency power package
Improved self-sealing fuel tanks	Emergency pressurization for fuel transfer
Steel liners added to aluminum hydraulic barrels	Armor

Table 7a Some Vulnerability Reduction Features used on the Fuel System of the A–10A, F/A–18A, and UH–60A Aircraft

A–10A	F/A–18A	UH–60A
Kill Mode: Fuel Supply Depletion		
Two self–sealing feed tanks located away from ignition sources	Two self–sealing feed tanks located away from ignition sources	Two self–sealing/crashworthy tanks located away from ignition sources
Short, self–sealing feed lines	Short, self–sealing feed lines	Short, self–sealing feed lines
Wing fuel used first	Wing fuel used first	Engine–mounted suction pumps
Most fuel lines located inside tanks	Most fuel lines located inside tanks	Cross feed capability
Cross feed capability located within tanks	Cross feed capability	
Redundant feed flow	Backup pump and redundant feed	
Kill Mode: Fire/Explosion		
Two self–sealing feed tanks located away from ignition sources	Two self–sealing feed tanks located away from ignition sources	Two self–sealing/crashworthy tanks located away from ignition sources
Short, self–sealing feed lines	Short, self–sealing feed lines	Short, self–sealing feed lines
Most fuel lines located inside tanks	Most fuel lines located inside tanks	Engine–mounted suction pumps
Open cell foam in all tanks	Open cell foam in wing tanks	Closed cell foam around tanks
Closed cell foam in dry bays around tanks	Closed cell foam under two fuselage tanks	
Draining and vents in vapor areas		
Kill Mode: Hydraulic Ram		
Minimum fuel in wings during combat	Minimum fuel in wings during combat	Crashworthy fuel tanks also hydrodynamic tolerant
	Damage control design of short length of inlet next to fuel tank	

Table 7b Some Vulnerability Reduction Features used on the Propulsion System of the A–10A, F/A–18A, and UH–60A Aircraft

A–10A	F/A–18A	UH–60A
Kill Mode: Loss of Thrust		
Two widely separated engines	Two engines	Two widely separated engines
Dual fire walls	Fire walls between engine, AMAD, and APU	Titanium fire walls
Fail–active fire detection with two shot fire extinguishing	Fire detection and one shot extinguishing system	Fire detection with two shot fire extinguishing
Engine case armor	Blade containment for fan, compressor, and turbine	Widely separated engine to transmission input modules
Separation between fuel tanks and air inlets	Inlet duct/fuel tank hydrodynamic ram damage control	No fuel ingestion
One engine out capability	One engine out capability	Good one engine out capability

Table 7c Some Vulnerability Reduction Features used on the Flight Control System of the A–10A, F/A–18A, and UH–60A Aircraft

A–10A	F/A–18A	UH–60A
Kill Modes: Disruption of Control Signal Path and Loss of Control Surfaces		
Two independent, separated mechanical flight controls with mechanical disconnects	Two flight control computers with four separated electrical signal lines to actuators	Two independent, separated mechanical flight controls with mechanical disconnects
Two rudders and elevators	Backup mechanical controls to tail	Tail rotor is stable if pitch rod is severed
Armor around stick where redundant controls converge		Spring drives tail rotor blades to fixed pitch setting if control signal is lost
		Controls are ballistically tolerant
Kill Modes: Loss of Control Power and Hydraulic Fluid Fire		
Two independent, separated hyd power subsystems	Two independent, separated hyd power subsystems with two circuits per subsystem	Two independent, separated, and shielded hyd power subsystems
A/C can be controlled without hyd power with mech controls and dual, electrically powered trim actuators	Rip–stop actuators	Third electrically driven backup can power either or both primary subsystems with quick disconnects and leak isolation valves
Less flammable hyd fluid	Less flammable hyd fluid	Less flammable hyd fluid
	Reservoir level sensing	

Table 7d Some Vulnerability Reduction Features used on the Air Crew System of the A–10A, F/A–18A, and UH–60A Aircraft

A–10A	F/A–18A	UH–60A
Kill Modes: Incapacitation or Death		
Pilot sits in a titanium/aluminum armor bathtub		Crashworthy armored seats and retention system
Spall shields between armor and pilot		Shatterproof cockpit window
Bullet resistant windscreen		Minimum–spall materials used in cockpit
Spall resistant canopy side panels		Kevlar armor to stop HEI fragments

Table 7e Some Vulnerability Reduction Features used on the Rotor Blade & Drive Train of the UH–60A Aircraft

UH–60A		
Kill Modes: Loss of Lubrication and Structural Damage		
Main Transmission	*Main rotor*	*Tail Rotor Drive System*
Modularized transmission eliminates exposed high speed shafts and multiple lube systems with exposed oil components	Rotor blades tolerant to HEI projectiles	Large vertical tail with log boom provides anti–torque in forward flight
Operates more than one hour after loss of all oil	Elastomeric hub with no lube, tolerant to HEI projectiles	Shaft supports provide damping for damaged shaft
Noncatastrophic failure allows autorotation		No bearings or lube in cross–beam rotor
		Tail rotor blades ballistically tolerant
		Damaged parts thrown away from the helicopter

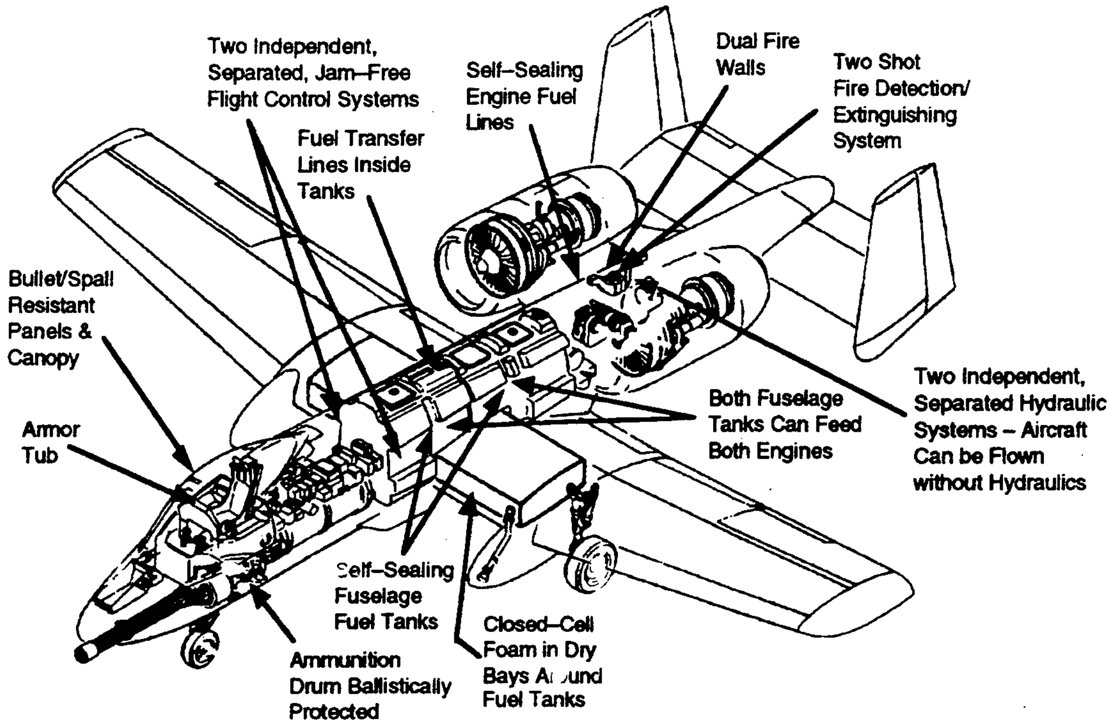

Fig. 1 Some Vulnerability Reduction Features on the A–10A Thunderbolt II [13]

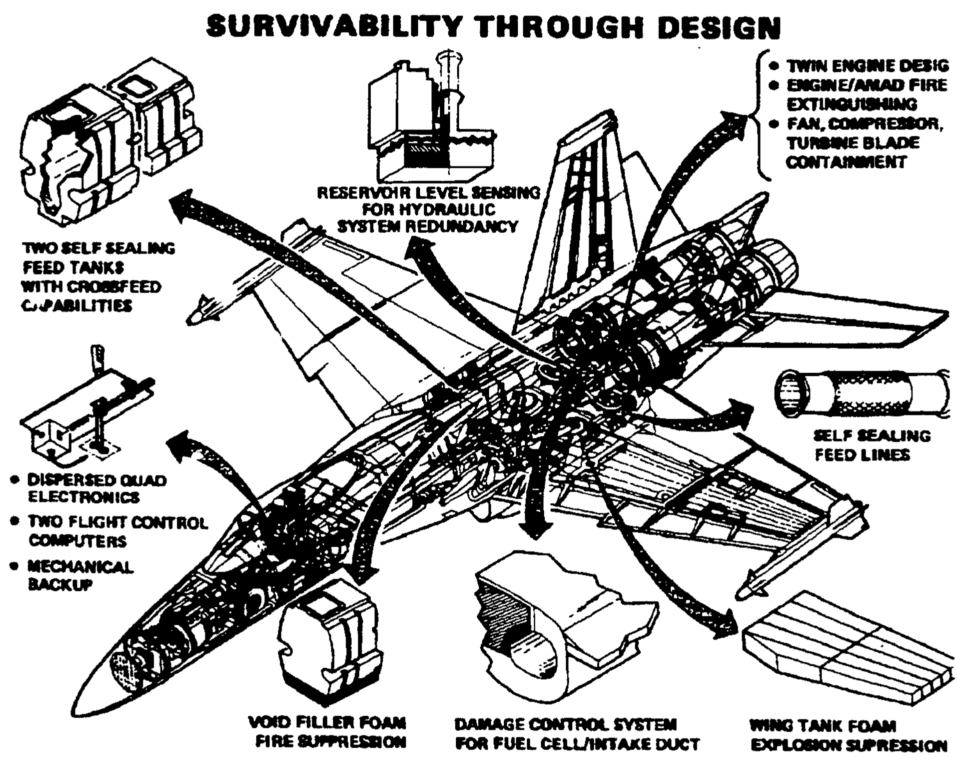

Fig. 2 Some Vulnerability Reduction Features on the F/A–18A (Courtesy of McDonnell Aerospace)

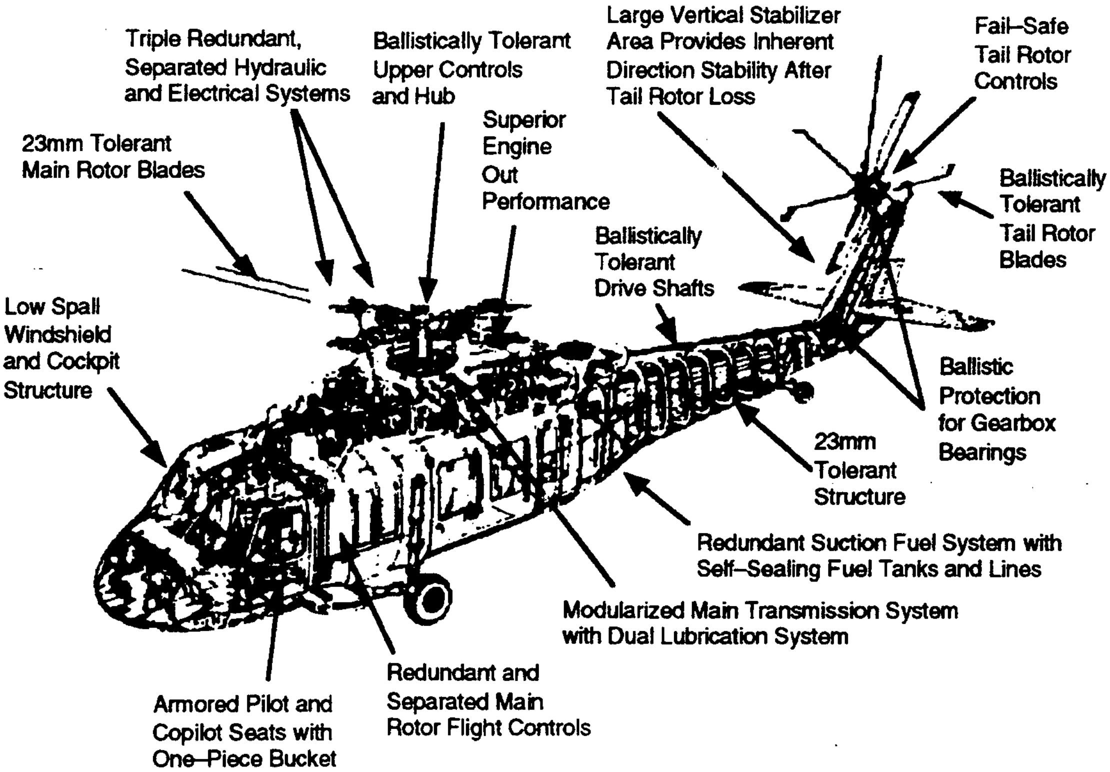

Fig. 3 Some Vulnerability Reduction Features on the UH–60A (Courtesy of Sikorsky Aircraft Division)

AIRLINE SAFETY & SECURITY: AN INTERNATIONAL PERSPECTIVE

Peter T. Reiss

International Federation of Airline Pilots' Associations

"ENHANCING AIRCRAFT SURVIVABILITY -- A VULNERABILITY PERSPECTIVE"

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NATIONAL DEFENSE INDUSTRIAL ASSOCIATION

Naval Postgraduate School
Monterey, California

AIRLINE SAFETY & SECURITY: AN INTERNATIONAL PERSPECTIVE

ADMIRAL GORMLEY, LADIES AND GENTLEMEN, IT IS WITH GREAT PLEASURE THAT I AGAIN SPEAK WITH YOU OF "THE VIEW FROM THE FLIGHT DECK" ON THE SUBJECT OF AIRLINE SAFETY AND SECURITY......YOUR INTEREST IS TRULY APPRECIATED. I NOTE THAT SINCE I HAD THE PRIVILEGE OF ADDRESSING MANY OF YOU IN ST. LOUIS IN OCTOBER OF 1993 ADPA AND NSIA HAVE FORMALLY JOINED TOGETHER BECOMING NDIA. MAY I CONGRATULATE YOU ON SO DOING.

AS THE FIELD OF INTERNATIONAL CIVIL AVIATION IS SUCH A HIGHLY VISIBLE AND THEREFORE OFTEN CHOSEN TARGET OF THE TERRORIST, WE IN THE BUSINESS OF COMMERCIAL AVIATION MUST ALWAYS STRIVE TO PROTECT THE LIVES OF OUR PASSENGERS, CREW, AND GROUND PERSONNE ; AND THE SAFETY OF OUR AIRCRAFT AND AIRPORTS REGARDLESS OF WHETHER THE THREAT IS ONBOARD THE AIRPLANE FROM A HIJACKING OR EXPLOSIVE DEVICE, A DEVICE PLANTED WITHIN OUR AIRPORT, OR FROM OUTSIDE THE AIRCRAFT OR AIRPORT IN THE FORM OF A MISSILE. <u>IT IS ONLY THROUGH COOPERATION, COORDINATION, AND COMMUNICATION</u> THAT THESE THREATS CAN BE MANAGED. TO THAT END, I WISH TO CONGRATULATE, ON BEHALF OF IFALPA, THE ORGANIZERS AND SPONSORS OF THIS SYMPOSIUM FOR THEIR EFFORTS. I AM VERY MUCH LOOKING FORWARD TO OUR UPCOMING SESSIONS.

THE SUBJECT OF AIRCRAFT SURVIVABILITY IS SO FUNDAMENTAL TO <u>OUR</u> MISSION OF SAFE TRANSPORTATION OF OUR PASSENGERS AND OUR FREIGHT REGARDLESS OF WHAT TOTALLY UNEXPECTED EVENTS MAY TAKE PLACE ON OUR FLIGHT, THAT WE CONSIDER IT TO BE ONE OF THE BASIC TECHNOLOGIES ON WHICH THE FUTURE OF OUR INDUSTRY DEPENDS.

I WOULD LIKE TO PARTICULARLY ACKNOWLEDGE PROF. BALL, WHO, THROUGH HIS TEXT, <u>THE FUNDAMENTALS OF AIRCRAFT COMBAT SURVIVABILITY ANALYSIS AND DESIGN</u>, CONTRIBUTED SO MUCH TO MY UNDERSTANDING OF THOSE FUNDAMENTALS AS THEY APPLY IN THIS PRESENTATION

I ADDRESS YOU TODAY ON BEHALF OF THE INTERNATIONAL FEDERATION OF AIR LINE PILOT'S ASSOCIATIONS OR **IFALPA**. IFALPA IS A WORLDWIDE FEDERATION OF PILOT REPRESENTATIVES OF 97 COUNTRIES AROUND THE WORLD. THE FEDERATION IS HEADQUARTERED IN LONDON SERVING PRIMARILY AS A TECHNICAL ORGANISATION <u>WITHOUT</u> A POLITICAL AGENDA.

IT MAY BE HELPFUL TO SET THE STAGE BY PROVIDING A BIT OF BACKGROUND ABOUT **IFALPA'S SECURITY COMMITTEE** AND ITS PURPOSE. IFALPA'S SECURITY COMMITTEE WORKS WELL DESPITE THE FACT THAT ITS MEMBERSHIP COMES FROM VERY DIVERSE BACKGROUNDS ACROSS THE

WORLD. THIS BECAUSE OF ITS SINGULARITY OF PURPOSE. THE PREMISES OF AVIATION SECURITY ARE SO SPECIFIC THAT WE ARE IN VERY CLOSE ACCORD ON VIRTUALLY ALL AVSEC PRINCIPLES SO CLOSELY RELATED TO THE SAFETY OF OUR PASSENGERS WHO ENTRUST THEIR LIVES AND THOSE OF THEIR LOVED ONES INTO OUR HANDS. MAY I INQUIRE AS TO HOW MANY OF YOU SUBCONSCIOUSLY COUNTED ON THAT TRUST WHEN YOU DEVELOPED YOUR TRAVEL PLANS FOR OUR SYMPOSIUM?

WE SPEAK WITH ESSENTIALLY ONE VOICE THAT IS IN MANY RESPECTS VERY CLOSE TO THOSE OF **THE INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO), THE INTERNATIONAL AIR TRANSPORT ASSOCIATION (IATA), AND AIRPORTS COUNCIL INTERNATIONAL (ACI).** HENCE, WE WORK IN VERY CLOSE ACCORD WITH THOSE ORGANISATIONS.

SANDRA MEADOWS, IN THE SEPTEMBER ISSUE OF "**NATIONAL DEFENSE**", STATED THAT "MORE U.S. SERVICE MEN HAVE LOST THEIR LIVES TO TERRORISTS DURING THE PAST 20 YEARS THAN HAVE BEEN KILLED IN COMBAT, ACCORDING TO PENTAGON ESTIMATES".

IN THE WORDS OF BRIG. **GEN. JAMES CONWAY, USMC**, DEPUTY DIRECTOR FOR COMBATING TERRORISM, JCS, "MILITARY COMMANDERS DEPLOYED OVERSEAS, PARTICULARLY, ARE ACUTELY AWARE THAT TERRORIST FORAYS AGAINST U.S. FORCES WILL NOT ONLY LEAD TO CASUALTIES BUT ALSO TO THE LOSS OF PUBLIC SUPPORT FOR MILITARY DEPLOYMENTS."

"POTENTIAL U.S. ENEMIES KNOW THAT THIS COUNTRY, DESPITE ITS OVERWHELMING MILITARY MIGHT, HAS A '**CRITICAL VULNERABILITY**'. BECAUSE THE AMERICAN PUBLIC CAN SEE EVENTS UNFOLD ON LIVE TV, U.S. ENEMIES KNOW THAT AT THE SIGHT OF BLOODSHED, AMERICANS WILL IMMEDIATELY QUESTION THE PURPOSE OF THAT MILITARY MISSION -- AND WHETHER IT IS WORTH U.S. LIVES. 'THAT MEANS A THIRD WORLD NATION CAN GET AT OUR NATIONAL POLICIES' BY DOMINATING THE SIX O'CLOCK NEWS, SAYS GEN. CONWAY".

AN ACT OF **TERRORISM**, OR EVEN AN ACCIDENT THAT IS PER- CEIVED TO HAVE BEEN RESULTING FROM AN ACT OF TERRORISM AGAINST OUR INDUSTRY SENDS THE PUBLIC SCURRYING TO THEIR TELEPHONES TO CANCEL THEIR AIR TRAVEL PLANS.

"TERRORISM -- THE THEATRE OF THE OBSCENE." I STRONGLY SUGGEST THAT WE -- THE MILITARY AND THE AIRLINE INDUSTRY -- HAVE A COMMON THREAT HERE OF MAJOR PROPORTION AND MASSIVE DIVERSE POTENTIAL IMPACTS. NOT ONLY DO WE BOTH LOSE LIVES; YOU LOSE PUBLIC SUPPORT; WE LOSE BUSINESS. THE PUBLIC, INCLUDING THE TRAVELING

PUBLIC, EXPERIENCES A PSYCHOLOGICAL IMPACT THAT CAN AND OFTEN DOES RESULT IN A REDUCTION OF THEIR FAITH IN GOVERNMENT AND INDUSTRY; MANIFESTING AS THE LOSS OF THE PEACE OF MIND AND A PART OF THAT DEEP FEELING OF INNER SECURITY HOPEFULLY EXPERIENCED BY A POPULATION. FURTHER, AVIATION SECURITY IS A NATIONAL SECURITY PROBLEM.

"MEETING SURVIVABILITY AND SAFETY CHALLENGES FOR THE 21ST CENTURY"...THERE HAS BEEN SINCE THE LOSS OF TWA 800 A FUNDAMENTAL SHIFT WITHIN THE UNITED STATES GOVERNMENT AND THE AVIATION INDUSTRY. THERE IS NOW AN AGREEMENT THAT THERE SHOULD BE A NEW BASELINE OF SECURITY; AN UPGRADING OF SECURITY WITHIN OUR INDUSTRY THAT SETS A NEW "BOTTOM RUNG OF THE LADDER", SO TO SPEAK. IN ACCORDANCE WITH THIS CONCEPT, THE BASELINE WORKING GROUP OF THE GORE COMMISSION WAS CREATED. AMONG THE RECOMMENDATIONS OF THIS GROUP (CONSISTING OF REPRESENTATIVES OF INVOLVED GOVERNMENT AGENCIES, AND VARIOUS INDUSTRY GROUPS) ARE: A BROAD EMPLACEMENT OF FAR MORE SOPHISTICATED EXPLOSIVES AND WEAPONS DETECTION SYSTEMS (COMPUTED TOMOGRAPHY AND UPGRADED X-RAYS), IMPROVED SELECTION AND TRAINING FOR THOSE WHO WILL BE OPERATING THE EQUIPMENT, AND ASSESSMENT OF THE VIABILITY OF ANTI-MISSILE DEFENSE SYSTEMS.

WE AT IFALPA BELIEVE THAT THE GREATEST SINGLE AVIATION THREAT IS THE SENSELESS DESTRUCTION OF AIRCRAFT IN FLIGHT; THIS GENERALLY, BUT CLEARLY NOT ALWAYS, DUE TO EXPLOSIVE DEVICES BROUGHT ON BOARD AIRCRAFT IN CARRY-ON AND CHECKED BAGGAGE.

RECALLING INTERPOL'S **TERRORISM STATISTICS** INDICATING BOMBINGS TO BE THE MODUS OPERANDI IN 35 PERCENT OF 1995 INCIDENTS, AND OUR INDUSTRY'S RECORD; I WOULD BELIEVE THIS TO BE A VERY MUCH ONGOING THREAT IN THE YEARS TO COME. THEREFORE, WE LOOK WITH PARTICULAR INTEREST AT INCORPORATION INTO AIRCRAFT DESIGN THE MEASURES WHICH FOCUS MOST DIRECTLY AT VULNERABILITY PERSPECTIVES ASSOCIATED WITH INFLIGHT INTERNAL EXPLOSIONS. HOWEVER, AS OUR INDUSTRY DOES FACE OTHER THREATS, AS WELL, WE MUST BROADEN OUR CONCERN TO INCLUDE VARIOUS OTHER DEFENSIVE MEASURES IN THE OVERALL FIELD OF INCORPORATION OF SECURITY INTO AIRCRAFT DESIGN, OR "ISAD".

IFALPA SUGGESTS THAT THE DEVELOPING AIRCRAFT TYPES BE EQUIPPED WITH SUITABLE CARGO HOLD BOMB PROOFING MODIFICATIONS WHICH PROVIDE PROTECTION TO ESSENTIAL CONTROLS AND HYDRAULIC LINES. WE STRONGLY ENDORSE THE **AIRCRAFT AND CONTAINER HARDENING PROGRAMS** OF THE FAA. WHILE THE AIRCRAFT HARDENING PROGRAM HOLDS

CONSIDERABLE PROMISE, ECONOMICS DICTATE THAT THE MAJORITY OF SUCH MEASURES WILL BE INCORPORATED INTO FUTURE AIRCRAFT AND POSSIBLY CERTAIN AIRCRAFT FLYING INTO THE HIGHER RISK THEATRES, RATHER THAN RETROFITTING EXISTING FLEETS OF AIRCRAFT. THESE MEASURES ARE THE TYPICAL VULNERABILITY REDUCTION TECHNIQUES, SUCH AS PROTECTION OF CRITICAL STRUCTURE, COMPONENTS, AND SYSTEMS, BOTH THROUGH HARDENING AND INCREASED REDUNDANCY.

A SENSIBLE APPROACH, WHICH SEEMS TO BE OF CONSIDERABLY LESS ECONOMIC AND OPERATIONAL IMPACT, IS THE **HARDENING OF BAGGAGE / CARGO HOLDS** OR THE HARDENING OF BAGGAGE CONTAINERS. TESTS HAVE BEEN RECENTLY CONDUCTED USING SURPLUSED AIRFRAMES, BOTH HERE AND IN THE UNITED KINGDOM. SEVERAL PROTECTIVE MATERIALS WERE LAYERED ONTO THE WALLS OF CARGO HOLDS WITH RESULTANT CONSIDERABLE MITIGATION OF THE DESTRUCTIVE EFFECTS OF THE TEST EXPLOSIVES. HARDENED CONTAINERS OF THE "LD-3" TYPE, COMMONLY USED IN WIDE-BODIED AIRCRAFT, WERE TESTED. THESE HARDENED CONTAINERS WERE QUITE EFFECTIVE. THERE NEED BE SOME FURTHER IMPROVEMENTS IN THE DOOR MECHANISMS, HOWEVER, FOR OPERATIONAL REASONS. SMALLER SIZED CONTAINERS FOR NARROW-BODIED AIRCRAFT ARE BEING DESIGNED AT THE PRESENT TIME. IT IS EXPECTED THAT BY THE END OF THE YEAR THERE WILL BE 20 TO 40 HARDENED CONTAINERS BEING OPERATIONALLY TESTED ON BOARD THE AIRCRAFT OF US AIRLINES. WE WOULD ENVISION THAT EVENTUALLY ONE OR TWO HARDENED CONTAINERS WILL BE DEPLOYED ON MANY AIRCRAFT THE WORLD OVER. THE REAL VALUE OF THE CONTAINERS IS THAT, DUE TO THEIR CAPABILITY OF WITHSTANDING A MODEST EXPLOSIVE CHARGE, WHEN IN COMBINATION WITH THE USE OF EXPLOSIVE DETECTION EQUIPMENT, THE MINIMUM QUANTITY OF EXPLOSIVE NECESSARY TO BE DETECTED IS RAISED TO A SIZE THAT PERMITS OPERATION OF THE EXPLOSIVE DETECTION EQUIPMENT AT A FAIRLY HIGH THROUGHPUT OF BAGS WHILE ENJOYING A LOW FALSE ALARM RATE. THIS MAKES IT OPERATIONALLY FEASIBLE TO ACCOMPLISH "100 PER CENT" DEPARTURE BAG CHECKING

ON A PERSONAL NOTE, IN VIEW OF THE BACKGROUND OF MANY OF YOU HERE TODAY, I SHOULD LIKE TAKE THE LIBERTY ONCE AGAIN, AS I DID FOUR YEARS AGO, <u>TO DIGRESS A MOMENT FROM MY PRESENTATION</u> ,................ TO SPEAK WITH YOU <u>NOT AS A REPRESENTATIVE OF IFALPA</u>, BUT AS PETER REISS; THE PERSON. THESE REMARKS ARE BEING DELIVERED TO YOU TODAY BY ONE WHO PERSONALLY FLEW MAC CONTRACT AND CRAF FLIGHTS OVER A PERIOD OF 27 YEARS, IN SUPPORT OF THE EFFORTS IN SOUTHEAST ASIA, EUROPE, AND THE PERSIAN GULF. I WOULD LIKE FURTHER TO SHARE WITH YOU A MATTER OF DEEP PERSONAL SIGNIFICANCE TO <u>ME</u>. IN MY 31 YEARS OF FLYING HEAVY TRANSPORT AIRCRAFT, THE <u>MOST</u> EMOTIONALLY AND

SPIRITUALLY REWARDING MOMENTS OF MY CAREER, WERE THE CRAF FLIGHTS BRINGING OUR PERSONNEL HOME FROM SAUDI ARABIA IN EARLY 1991. I SHALL ALWAYS FEEL A QUIET AND INTENSE PRIDE. NOW, BACK TO MY PRESENTATION......

I WILL BRIEFLY TOUCH UPON **OTHER VULNERABILITY REDUCTION CONSIDERATIONS** THAT IFALPA RECOMMENDS: THE DEVELOPMENT OF IMPROVED SMOKE/FIRE WARNING DEVICES AND EXTINGUISHING EQUIPMENT IN THE CARGO HOLDS; DIRECTION OF AIR-FLOW AWAY FROM THE COCKPIT AREA; AND DESIGN FOR EASE OF SEARCH / INHIBITION OF CONCEALMENT. THESE CONSIDERATIONS ARE UNDER STUDY BY THE ISAD WORKING GROUP AT THE INTERNATIONAL CIVIL AVIATION ORGANIZATION, AND WILL LIKELY BE INCORPORATED INTO THE APPROPRIATE ANNEXES IN THE NEAR FUTURE.

WHEN VULNERABI! !TY REDUCTION CONSIDERATIONS LEAD TO **RECOMMENDED MODIFICATIONS** TO THE AIRCRAFT ITSELF, WE MUST ALSO ADDRESS POSSIBLE RESULTANT COST TO THE MANUFACTURER, AND, SUBSEQUENTLY TO THE OWNER AND OPERATOR; AND THE POTENTIAL IMPACT ON THE OPERATION OF THE AIRCRAFT'S SYSTEMS THEMSELVES. LET US LOOK AT THE AFTERMATH OF THE EXPLOSION OF TWA 800. WHILE I HAVE NO PARTICULAR JUDGMENT REGARDING, OR SUGGESTION AS TO THE APPROPRIATENESS OF, THE URGENT RECOMMENDATIONS EARLIER THIS YEAR OF THE NATIONAL TRANSPORTATION SAFETY BOARD, I SEE MANY POTENTIAL IMPACTS THEREFROM. I AM SPECIFICALLY REFERENCING, AMONGST OTHERS, THE CARRIAGE OF EXTRA FUEL, REDUCED USE AND MOVING OF AIR CONDITIONING PACKS, AND MOVING OF THE FUEL PUMPS.

THE **COST OF RETROFIT** -- SEVERAL MILLIONS OF DOLLARS EACH FOR THE 1,000+ BOEING 747'S IN SERVICE TODAY MUST BE CAREFULLY CONSIDERED. IFALPA SUGGESTS THAT THE COST OF CARRIAGE OF NON-USABLE FUEL IN THE CENTER TANK -- IN THE ECONOMICS ARENA -- IN REDUCED USEFUL LOAD CARRYING CAPABILITY, AND THE INCREASE IN THE LIKELIHOOD OF FIRE IN A CATASTROPHIC LANDING ACCIDENT MUST BE <u>VERY</u> CAREFULLY STUDIED BEFORE ANY APPLICATION OF A MANDATED POLICY IS EVEN <u>CONSIDERED</u>, LET ALONE SUGGESTED OR PROMOTED. I WOULD MOST FERVENTLY HOPE THAT ANY SUCH VULNERABILITY REDUCTION MEASURES ARE BASED UPON VERY HARD EVIDENCE THAT SUCH MEASURES ARE NECESSARY AND APPROPRIATE FOR THE TRUE RISK INVOLVED, AND ARE NOT A RESPONSE TO OTHER PRESSURES. IN OUR STUDIED OPINION, THE CAUSE OF THE CATASTROPHIC INFLIGHT BREAK-UP OF TWA 800 IS STILL A VERY MUCH UNSOLVED QUESTION.

MAY I SUGGEST THAT THE MORE RECENT RECOMMENDATIONS OF THE

NATIONAL TRANSPORTATION SAFETY BOARD TO REDUCE THE EXPLOSIVE POTENTIAL OF THE FUEL ULLAGE, OR VAPOR, WOULD SEEM TO BE LESS INTRUSIVE INTO THE OPERATIONAL AND ECONOMIC ARENAS. AMONG THESE ARE INTRODUCTION OF COOLED FUEL INTO THE CENTER TANK, INERTING THE TANK WITH A NON-REACTIVE GAS, AND INSULATION OF THE TANK TO PROTECT IT FROM THE HEAT GENERATED BY THE AIR CONDITIONING UNITS. HOWEVER, EVEN THESE MEASURES EACH APPEAR TO CREATE THEIR OWN OPERATIONAL PROBLEMS (FOR EXAMPLE, THE OBIGGS SYSTEM ON THE C-17). FURTHER, THERE ARE SAFETY-DIMINISHING IMPACTS AS WELL TIED TO EMPLOYMENT OF THESE PROPOSALS.

WHILE OUR SYMPOSIUM IS FOCUSED ON THE VULNERABILITY PERSPECTIVE, PLEASE BEAR WITH ME WHILE I DIGRESS TO A **SUSCEPTIBILITY** MATTER FOR A MOMENT, AS I WISH TO MENTION TO YOU A KEY ASPECT OF THE NEW SECURITY PARADIGM THAT IS BEING DEVELOPED: PROFILING. WE STRONGLY SUPPORT THE CONCEPT OF "**PROFILING**" OF PASSENGERS. OUR RESPONSES MUST BE THREAT-DRIVEN AND SPECIFIC. IN 1995, MEMBER AIRLINES OF THE INTERNATIONAL AIR TRANSPORT ASSOCIATION CARRIED 1.3 BILLION PASSENGERS WORLDWIDE. THERE WERE FIVE HIJACKINGS THAT INVOLVED REAL WEAPONS. TEN PERPETUATORS WERE INVOLVED. TEN OUT OF 1.3 BILLION.... THE RESOURCES AVAILABLE TO OUR INDUSTRY ARE NOT LIMITLESS. THEREFORE, WE MUST TARGET PRIMARILY ON THE HIGHER THREAT AREAS OR INDIVIDUALS, BE IT LOOKING FOR WEAPONS OR BE IT LOOKING FOR EXPLOSIVES -- INCLUDING THOSE IN PASSENGER BAGGAGE, CARRY-ON OR CHECKED.

WE SHARE WITH LAW ENFORCEMENT AGENCIES THE WORLD OVER THE CONCEPT THAT **INTERVENTION BY GROUND FORCES** DURING A HIJACKING IS ONLY A LAST RESORT, ONLY TO BE PERFORMED WHEN ALL ELSE HAS FAILED. WE FURTHER RECOGNIZE THE UNIQUE TACTICAL NATURE OF THIS ACTION, AND THE CRITICAL NEED OF HAVING ONLY HIGHLY AND SPECIALLY TRAINED TEAMS PERFORMING THIS SURGICAL AND EXTREMELY CHALLENGING OPERATION. MAY I SUGGEST THAT HISTORY HAS SHOWN THE POTENTIAL COST AMPLIFICATION OF AN INCIDENT SHOULD AN INTERVENTION BY GROUND FORCES GO AWRY. ON THE OTHER HAND, I SHOULD LIKE TO NOTE THAT THERE ARE EXCELLENT EXAMPLES OF THE VALUE AND CAPABILITY OF A HIGHLY TRAINED AND QUALIFIED SPECIAL OPERATIONS GROUP. THE UNITED STATES IS TRULY TO BE COMMENDED FOR THEIR ATTENTION TO ALL THE DETAILS AND EXPENDITURES NECESSARY TO MAINTAIN IN TOP OPERATIONAL CONDITION THE UNITS AVAILABLE FOR AN INTERNAL INTERVENTION, AND THOSE UNITS AVAILABLE FOR AN EXTRA-TERRITORIAL OPERATION (HERE I SPECIFICALLY REFERENCE GEOGRAPHIC EXTRATERRITORIALITY, AS A UNITED STATES REGISTERED AIRCRAFT IS, REGARDLESS OF LOCATION, UNITED STATES TERRITORY).

I SHOULD LIKE TO SHARE WITH YOU **AN INCIDENT** THAT TOOK PLACE DURING THIS PAST YEAR. ITS NARRATION, WHILE AMUSING, IS FURTHERMORE A GOOD ILLUSTRATION OF HOW THE SYSTEM WORKS.

AN AIRCRAFT OPERATING INTO AN EASTERN UNITED STATES CITY WAS DELAYED FOR FORTY MINUTES BY WEATHER, RESULTING IN A PLANNED TWENTY-MINUTE OUTBOUND DELAY. SHORTLY BEFORE THIS PLANNED DEPARTURE, A PASSENGER SEATED IN THE MAIN CABIN OF THE AIRCRAFT, WHO WAS DISTURBED BY THIS DELAY MADE THE REMARK TO AN ATTRACTIVE YOUNG WOMAN SEATED NEXT TO HIM, "WELL, I GUESS THAT THEY HAVEN'T FOUND MY BOMB YET". SHE, BEING QUITE STARTLED, RATHER THAN BEING IMPRESSED AS HE HAD HOPED, ASKED HIM WHAT HE HAD JUST SAID. HE REPEATED "WELL, I GUESS THAT THEY HAVEN'T FOUND MY BOMB YET". THIS TIME OTHERS HEARD HIS REMARK. SHE WAS QUITE DISTURBED, AND INQUIRED OF HIM AGAIN, WHEREUPON HE JUST SAT THERE IN HIS HARVARD BUSINESS SCHOOL SWEATSHIRT AND SMIRKED. SHE THEN WENT TO A FLIGHT ATTENDANT, AND -- WE ALL KNOW HOW THE THE CHAIN OF COMMAND WORKS -- THE CAPTAIN WAS ADVISED.

WELL, IT SO HAPPENS THAT THE COPILOT IS A MEMBER OF THE SECURITY COMMITTEE FOR THAT AIRLINE AND IS A FORMER POLICE OFFICER. WITHIN SEVERAL MINUTES HE AND OUR SELF-STYLED COMEDIAN WERE IN THE TERMINAL DISCUSSING THE MATTER. A MOMENT LATER, OUR SUSPECT WAS IN CONTINUED DISCUSSION WITH AN FBI AGENT AND TWO 6' 6" LOCAL POLICE OFFICERS; AND A BOMB DOG. HE FLATLY AND VEHEMENTLY DENIED HIS STATEMENTS; THEY USUALLY DO! HIS FIVE ACCOMPANYING PASSENGERS, INCLUDING HIS BOSS AND HIS BOSS' BOSS WHO WERE IN THE FIRST CLASS CABIN OF THE AIRCRAFT, SOON JOINED THEM WITH ALL OF THEIR BAGGAGE.

THE DOG'S PART OF THE CONVERSATION IS THAT HE ALERTED WITH GREAT INTEREST AND ENTHUSIASM ON A SET OF GOLF CLUBS. IN MORE WAYS THAN ONE, THESE WERE NOT JUST ANY ORDINARY SET OF GOLF CLUBS, SO IT TURNED OUT. WE WILL GET TO THAT...... THE GOLF CLUBS SOON WENT ON THEIR LAST RIDE: TO A REMOTE AREA OF THE AIRPORT. THERE, THEY WERE ASSISTED BY A 1/2 POUND DISRUPTER CHARGE -- INTO THE GREAT BEYOND.

WELL, IT TURNED OUT THAT THESE SIX PASSENGERS WERE ON THEIR WAY TO A MAJOR GOLF TOURNAMENT IN PHOENIX -- 1,200 MILES DISTANT. THE FLIGHT WAS DELAYED FOR AN HOUR AND A HALF, THUS PREVENTING THE AIRCRAFT FROM GETTING TO PHOENIX IN TIME TO FLY A FULL LOAD OF 186 PASSENGERS BACK TO THE EASTERN CITY THAT NIGHT. THIS MEANT THAT IN ADDITION TO BEING CHARGED WITH A FEDERAL CRIMES ABOARD AIRCRAFT STATUTE, OUR "WISE MAN" HAD TO REIMBURSE THE AIRLINE FOR ALL ASSOCIATED LOST REVENUE -- PLACING THOSE 186 PASSENGERS ONTO OTHER AIRLINES, ETC -

LIKELY WELL OVER $20,000.

<u>OH, YES</u>... YOU WONDER ABOUT THOSE GOLF CLUBS? WELL, THEY WERE A $6,000 SET OF GRAPHITE CLUBS... AND <u>WHOSE</u> WERE THEY? YES, YOU GUESSED IT -- THEY BELONGED TO HIS BOSS.

I HAVE OFTEN WONDERED <u>IF</u>, WHEN HE EXPLAINED TO HIS WIFE HOW THEY WERE SUDDENLY $20,000 IN DEBT, HE WAS WITHOUT A JOB AND FACING CONVICTION FOR A FEDERAL CRIME, SHE COMMENTED TO HIM ABOUT HOW SHE HAD SOMETIMES WONDERED JUST HOW LONG IT WOULD BE BEFORE HIS BIG MOUTH WOULD GET HIM INTO SERIOUS TROUBLE... . MAY I SUGGEST THAT THAT YOUNG MAN HAS NOW A MUCH CLEARER AWARENESS OF HOW THE SYSTEM WORKS!

I WILL MENTION BRIEFLY TWO AREAS OF <u>REAL</u> CONCERN TO OUR SECURITY COMMITTEE.

FIRST, **ILLICIT CROSS-BORDER MOVEMENT OF NUCLEAR MATERIAL AND OTHER RADIOACTIVE SOURCES**. MAY I SUGGEST THAT THIS TRAFFICKING AND ALL OF ITS POTENTIAL RAMIFICATIONS MAY WELL BECOME ONE OF THE GREATEST THREAT AREAS BY WHICH WE ARE CONFRONTED. MAY WE FURTHER SUGGEST THAT THE SCOPE AND THE DEGREE OF THREAT IS INCREASING AT AN EXPONENTIAL RATE, ESPECIALLY EMANATING FROM THE FORMER SOVIET UNION AND CERTAIN AREAS IN EASTERN EUROPE.

THE INTERNATIONAL ATOMIC ENERGY AGENCY ESTABLISHED A GROUP OF SPECIALISTS FROM A NUMBER OF INTERNATIONAL ORGANISATIONS, INCLUDING INTERPOL, EUROPOL, EURATOM, <u>IFALPA</u>, THE WORLD CUSTOMS ORGANISATION, IATA, AND SEVERAL OTHERS TO DEVELOP RECOMMENDATIONS AND ASSIST IN THEIR IMPLEMENTATION IN THE AREA OF CONTROL OF ILLICIT CROSS-BORDER TRANSFER OF NUCLEAR AND RADIOACTIVE MATERIALS. OUR RECOMMENDATIONS WERE PRESENTED, WITH THE FULL BACKING OF THE IAEA, TO THE "GROUP OF 8" AT THE MOSCOW SUMMIT THIS YEAR.

THE <u>TOTAL LACK OF AWARENESS</u> OF SOME OF THE SMUGGLERS AS REGARDS THE DANGERS OF SIMPLY CARRYING THESE MATERIALS CANCELS OUT EVEN THE BASIC INSTINCTS OF SELF-SURVIVAL. THE DANGERS TO OUR PASSENGERS, CREWS, AND INDUSTRY RANGE FROM DISASTROUS <u>PERSONAL</u> EXPOSURE TO A CONTAMINATED $160,000,000 AIRCRAFT BEING PLACED OUT OF SERVICE FOR 15 YEARS. MAY I ASK EACH OF YOU HERE TODAY TO IMAGINE, FOR A MOMENT, IF YOU WOULD, A TRAVELER WITH A KILO OF CESIUM-137 IN HIS BRIEFCASE SEATED NEXT TO YOU ON AN EIGHT-HOUR FLIGHT ....<u>IMAGINE</u> THE <u>DISASTROUS</u> CONSEQUENCES TO <u>YOU</u>....

WE FORECAST AS WELL A THREAT OF ONBOARD PRESENCE -- AS A WEAPON -- OF CHEMICAL AND BIOLOGICAL MATERIALS. AS A REPRESENTATIVE OF THE JAPANESE DELEGATION SAID LAST AUTUMN AT THE INTERPOL TERRORISM SYMPOSIUM, "IT IS POSSIBLE FOR EVERY MOTIVATED TERRORIST TO USE THOSE KIND OF WEAPONS NOWADAYS". AS THE CHIEF OF THE COUNTER-TERRORIST UNIT AT INTERPOL (AN AMERICAN FBI AGENT SECUNDED THERETO) SAID, "THE ISSUE OF WMD IS NOT A MATTER OF 'IF', BUT '<u>WHEN</u>' AND '<u>HOW OFTEN</u>' ".

WE ARE CONVINCED THAT THE SOPHISTICATION OF CERTAIN OF THOSE WHOM ARE DEDICATED TO ACTS AGAINST OUR INDUSTRY, BE THEY OF STRAIGHT CRIMINAL NATURE, OR BE THEY ACTS OF TERRORISM, WILL INCREASE DRAMATICALLY. THE LEVEL OF EFFECTIVENESS OF OUR MEASURES MUST BE DEVELOPED TO A DEGREE THAT WILL CONTINUALLY EXCEED THE CAPABILITY OF "THE BEST AND THE BRIGHTEST" OF THIS TRADE.

IT IS ESSENTIAL THAT WE HAVE A COORDINATED PROACTIVE APPROACH IF WE ARE TO SUCCEED IN MANAGING THE THREAT. THIS REQUIRES INFORMATION AND INTELLIGENCE.

"STRENGTH THROUGH INDUSTRY AND TECHNOLOGY"..... ON THURSDAY I WAS AT OUR LAYOVER HOTEL IN TOKYO, READING THE JAPAN TIMES. I HAD JUST SPENT SEVERAL HOURS WORKING ON THIS PRESENTATION. A THOUGHT CAME TO MIND AS I READ ABOUT CHUCK YEAGER'S FLIGHT OF CELEBRATION, IN THE F-15, OF THE 50TH ANNIVERSARY OF HIS BREAKING THE SOUND BARRIER IN THE X-1. YOU ALL HAVE COME A LONG WAY DURING THESE LAST FIFTY YEARS IN AIRCRAFT VULNERABILITY REDUCTION TECHNOLOGY. WE ON THE COMMERCIAL SIDE HAVE CERTAINLY BENEFITED THEREFROM, AS HAS THEREBY <u>EVERY SINGLE</u> PASSENGER WHO RIDES ON OUR JET TRANSPORTS TODAY. SOMETIMES THERE SEEM TO BE LOTS OF FOLKS WHO FORGET THAT.....

I SHOULD LIKE TO DIGRESS AT THIS POINT FROM THE VULNERABILITY PERSPECTIVE TO ONE <u>ESPECIALLY</u> IMPORTANT AREA OF AVIATION <u>SAFETY</u>.... A <u>FUNDAMENTAL</u> THAT ENTERS INTO <u>EVERY SINGLE</u> ASPECT OF AVIATION SECURITY AND, IN FACT, <u>EVERY</u> ASPECT OF <u>TRANSPORTATION</u> SAFETY. THAT IS **TEAMWORK**. BE IT ON THE FLIGHT DECK -- AS PART OF THE DOMAIN OF CREW RESOURCE MANAGEMENT, OR IN THE STUDY AND IMPLEMENTATION OF ISSUES OF THREAT RESPONSE -- LONG TERM SUCH AS VULNERABILITY REDUCTION TECHNOLOGY AND ITS IMPLEMENTATION; OR SHORT TERM -- <u>TEAMWORK</u> IS <u>ESSENTIAL</u>. BASED IN PART ON OBSERVATION DURING MY 30 YEARS OF WORK IN AVIATION SECURITY, I AM CONVINCED THAT IT IS THROUGH THE **<u>INCREASED JOINT INDUSTRY-GOVERNMENT EFFORTS</u>**, DOMESTICALLY AND INTERNATIONALLY, THAT THE IMPACT OF THIS

ESSENTIAL COMPONENT IS MAXIMIZED. IT IS THROUGH OUR COMING TOGETHER AT SYMPOSIUMS SUCH AS THIS THAT WE FORM THE NETWORKS THAT FACILITATE OUR UNDERLYING SUCCESS AND OUR OVERALL PROGRESS. I CANNOT STRESS TOO STRONGLY THE IMPORTANCE OF TEAMWORK -- OF TEAMWORK AND COOPERATION IN THE LONG-TERM SUCCESS OF TRANSPORTATION SAFETY AND SECURITY. I WISH TO CITE THE COMMENTS OF OUR KEYNOTE SPEAKER, JOHN GOGLIA FROM THE NATIONAL TRANSPORTATION SAFETY BOARD, THIS MORNING REGARDING HUMAN FACTORS AS AN EXCELLENT REVIEW OF THE INTERRELATIONS BETWEEN HUMAN FACTORS AND COMMUNICATION IN AVIATION SAFETY IN OUR GLOBAL AVIATION FAMILY.

IN CLOSING, I MAKE ONE REQUEST ON BEHALF OF IFALPA. OUR REQUEST IS THAT YOU LOOK UPON US AS A *RESOURCE, A RESOURCE TO BE CALLED UPON AS PART OF THE TEAM. WE HAVE FOR MANY YEARS SERVED, AND WE CONTINUE TO SERVE, AS A PART OF THE GOVERNMENT AND INDUSTRY AVIATION SECURITY TEAM.*

AGAIN, WE APPRECIATE YOUR INCLUSION OF US IN YOUR SYMPOSIUM, AND I INVITE YOUR QUESTIONS THIS AFTERNOON DURING OUR PANEL DISCUSSION.

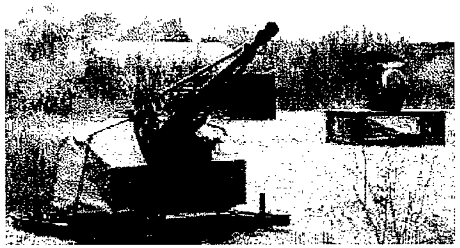
LADIES AND GENTLEMEN, THANK YOU FOR YOUR KIND ATTENTION.

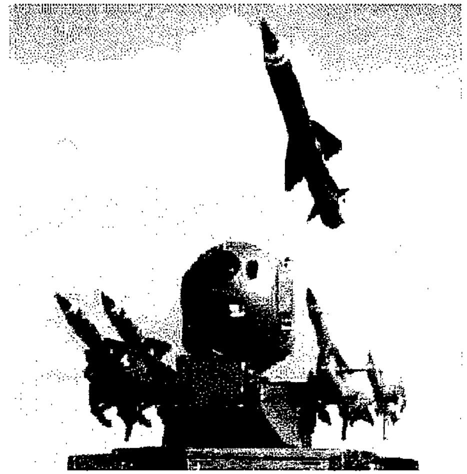
Vulnerability Reduction in Army Aviation

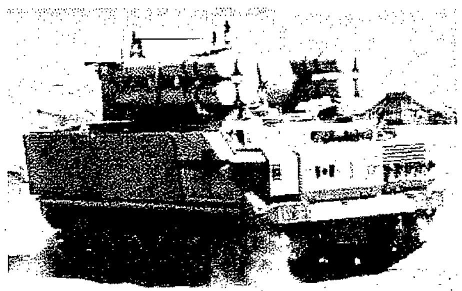
Brigadier General Burke
Deputy Commanding General
United States Army Aviation Center
21 Oct 97

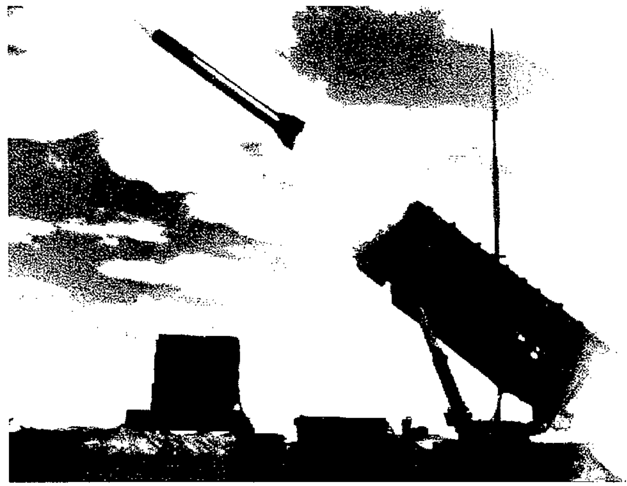
ARMY AVIATION WARFIGHTING CENTER

Radar Directed Threats

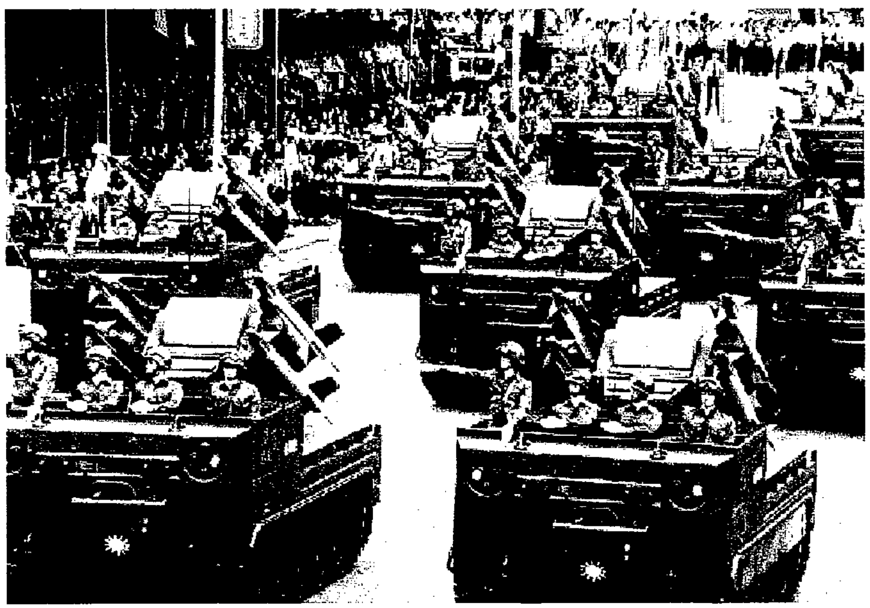




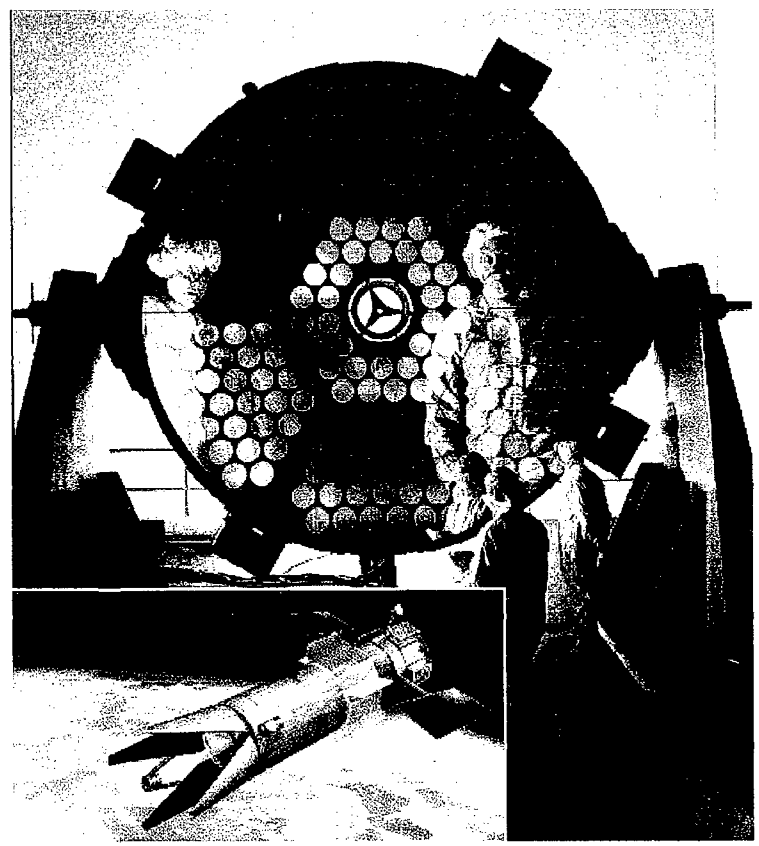




Infrared Threats



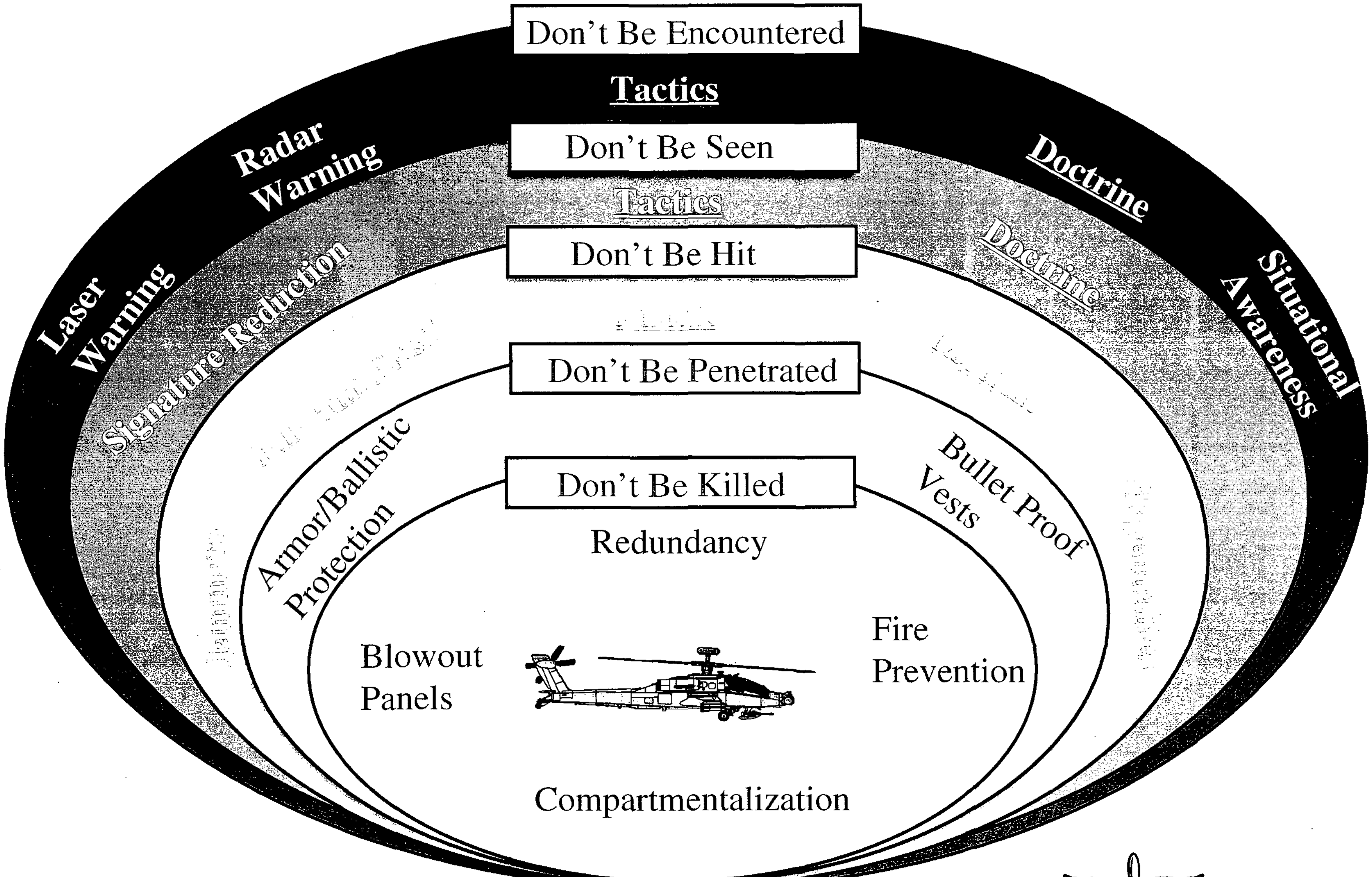
Directed Energy Threats



We Train Crews to Operate in Varied Environments

- Multiship
- Low Level
- In Low Visibility/At Night
- In the Face of the Enemy

Chain of Survivability



Don't Be Encountered

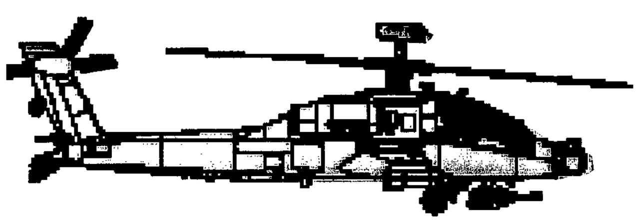
- Force Protection
- Counter Reconnaissance
- Security
- Situation Awareness
- Laser and Radar Warning

Don't Be Seen

- Mission Planning
- Shared Situation Awareness
- Extended Range Multi-Spectral Sensors
- Fire and Forget Missiles
- Low Observable Technology
- Tactics, Techniques and Procedures
- Night/Adverse Weather Capability

Don't Be Hit

- Aided Targeting
- Extended Range Point Munitions
- Integrated ASE, Tactics Expert Functions
- Reduced Signatures
- Fire and Forget Weapons
- Tactics, Techniques and Procedures
- Maneuverability and Agility
- Jammers



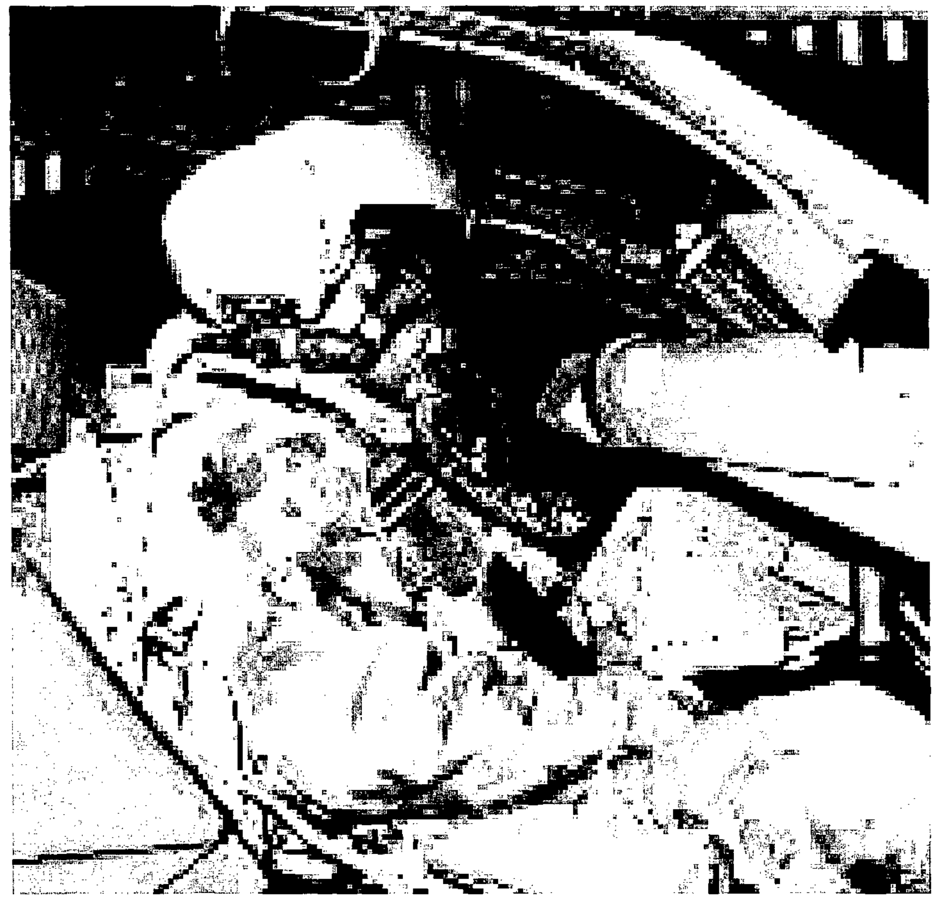
Don't Be Penetrated

- Hardening (Ballistic, EO, Directed Energy, Nuclear, Biological, Chemical)
- Tactics, Techniques and Procedures
- Onboard Diagnostics
- Self Sealing/Nitrogen Inerting Fuel Cells

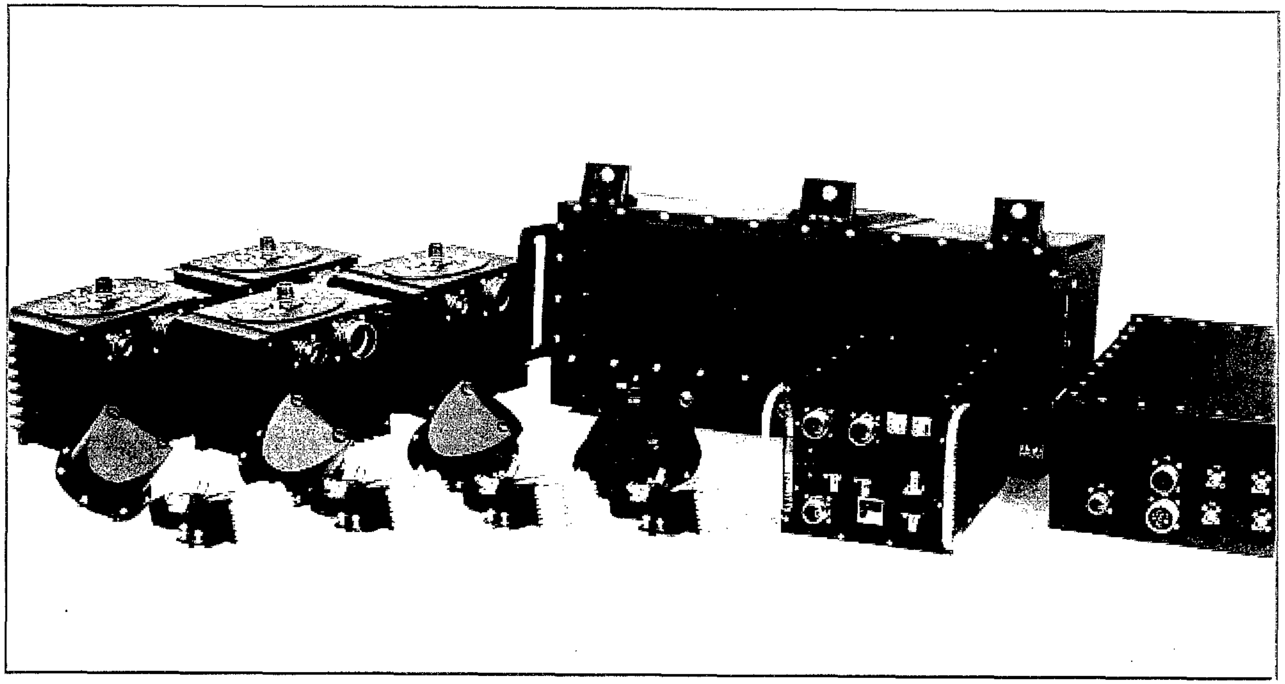
Don't Be Killed

- Redundant Systems
- Vertical Crash Impact Protection
- Fire Retarding System
- Autorotation/Survivable Landing Capability
- Air Bags, Crew Retention Systems
- Crew Survival Vests/Radios
- Crew Extraction Capability
- Survivable Cockpit
- Blow Out Panels

Air Warrior Equipment

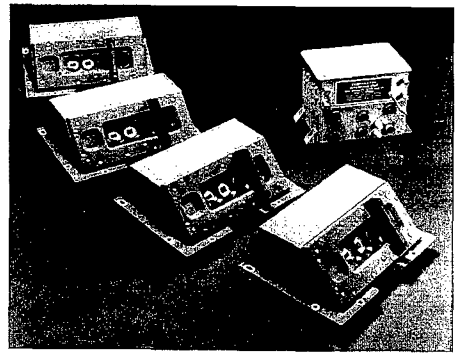


Suite of Integrated Radio Frequency Countermeasures



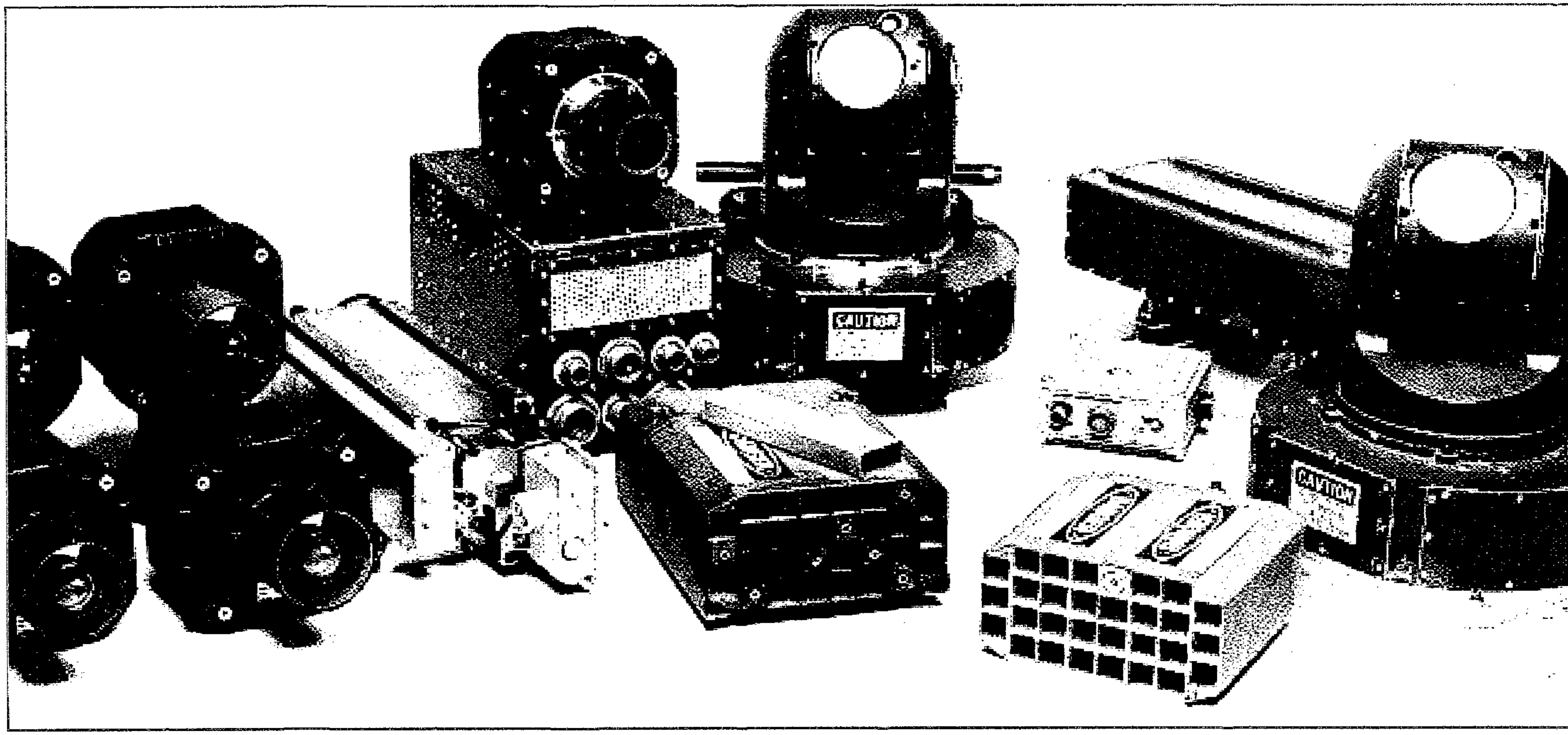
AN/ALQ -211
Suite of Integrated Radio Frequency Countermeasures

AN/AVR-2A
Laser Warning



Suite of Integrated Infrared Countermeasures

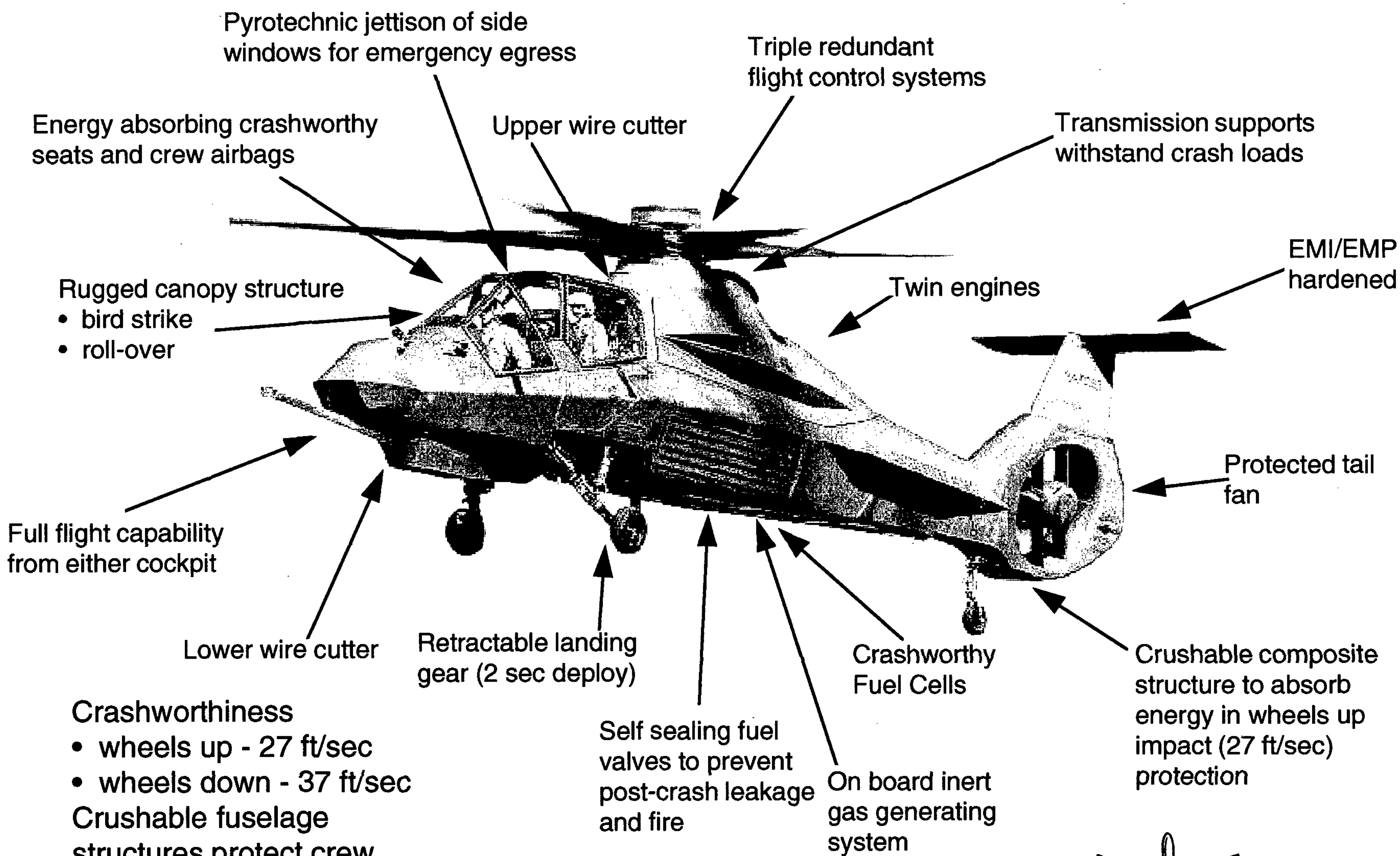
AN/ALQ-212



ARMY AVIATION WARFIGHTING CENTER

RAH-66 Comanche

Vulnerability Reduction



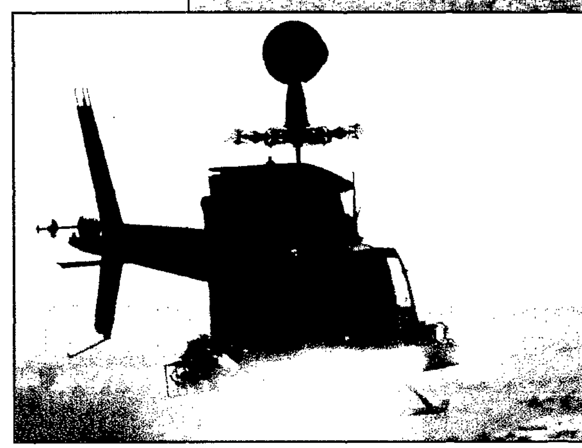
Crashworthiness
- wheels up - 27 ft/sec
- wheels down - 37 ft/sec

Crushable fuselage structures protect crew

ARMY AVIATION WARFIGHTING CENTER

Comanche Detectability Comparison (Radar)

Radar Detectability
- Front Sector



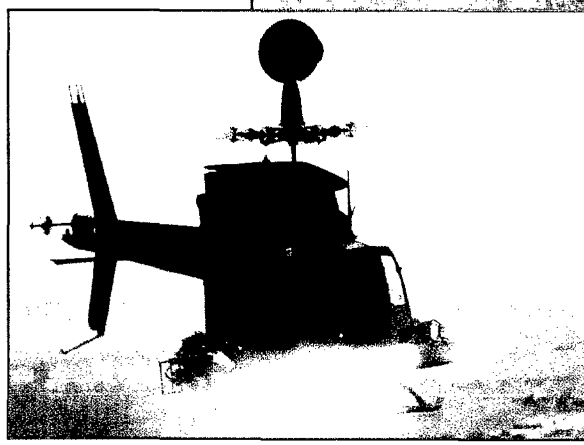
295 Times Smaller! THAN

35 Times Smaller! THAN

ARMY AVIATION WARFIGHTING CENTER

Comanche/ Detectability Comparison (Acoustic)

Acoustic
- Front Sector
- Moderate Ambient

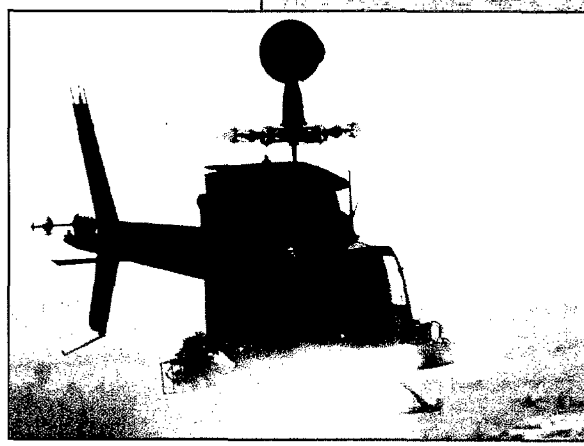


6 Times Quieter! THAN

1.8 Times Quieter! THAN

Comanche/ Detectability Comparison (Infrared)

Infrared
- Side sector
- Source signature
- No solar load
- Stinger



3.9 Times Cooler! THAN

1.9 Times Cooler! THAN

Comanche/ Detectability Comparison (Visual)

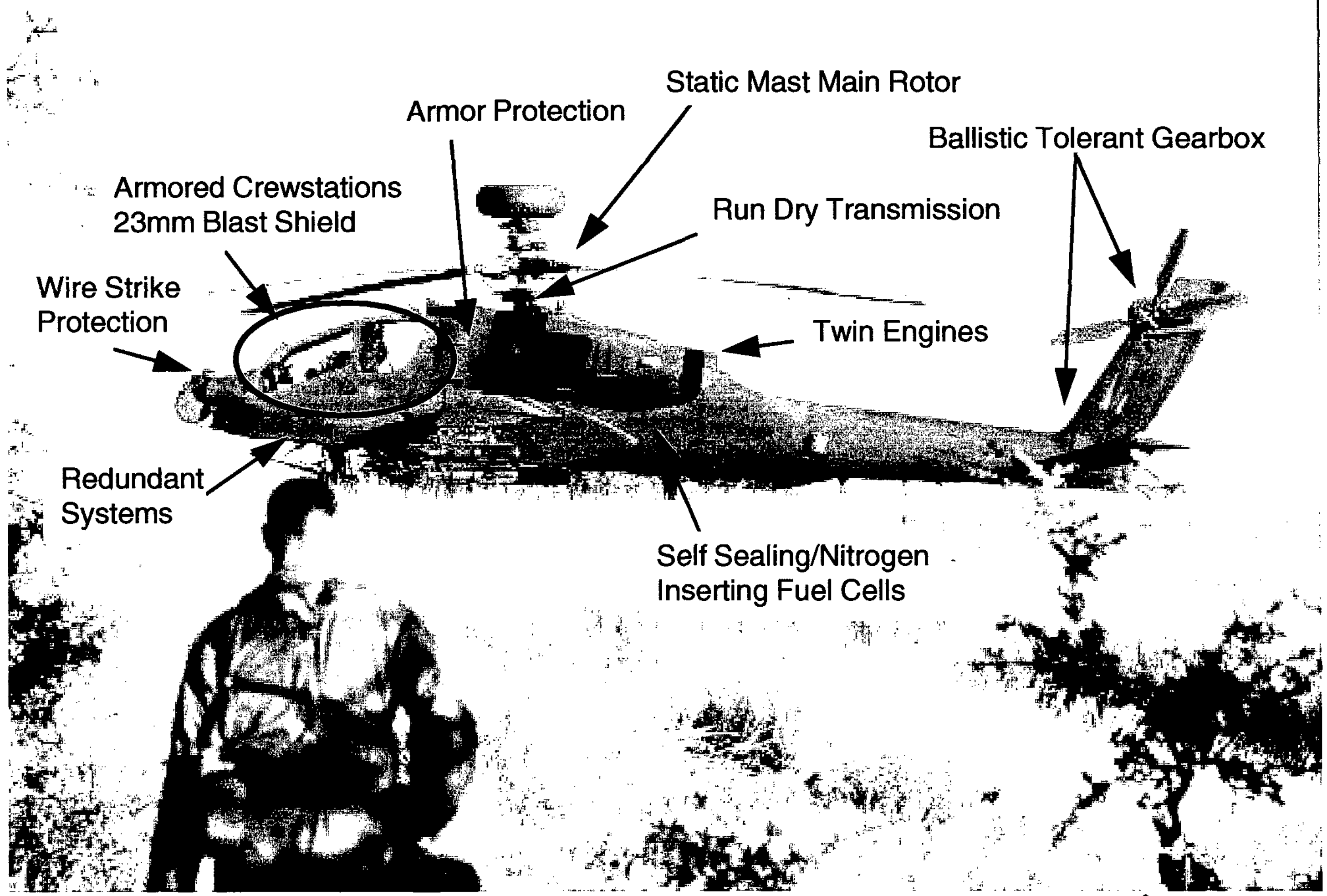
Visual
- Front Sector
- Unaided eye
- Terrain Background
- Sector search

1.2 Times Smaller!

0.9 Times Smaller!

119

AH-64D Longbow Hardening

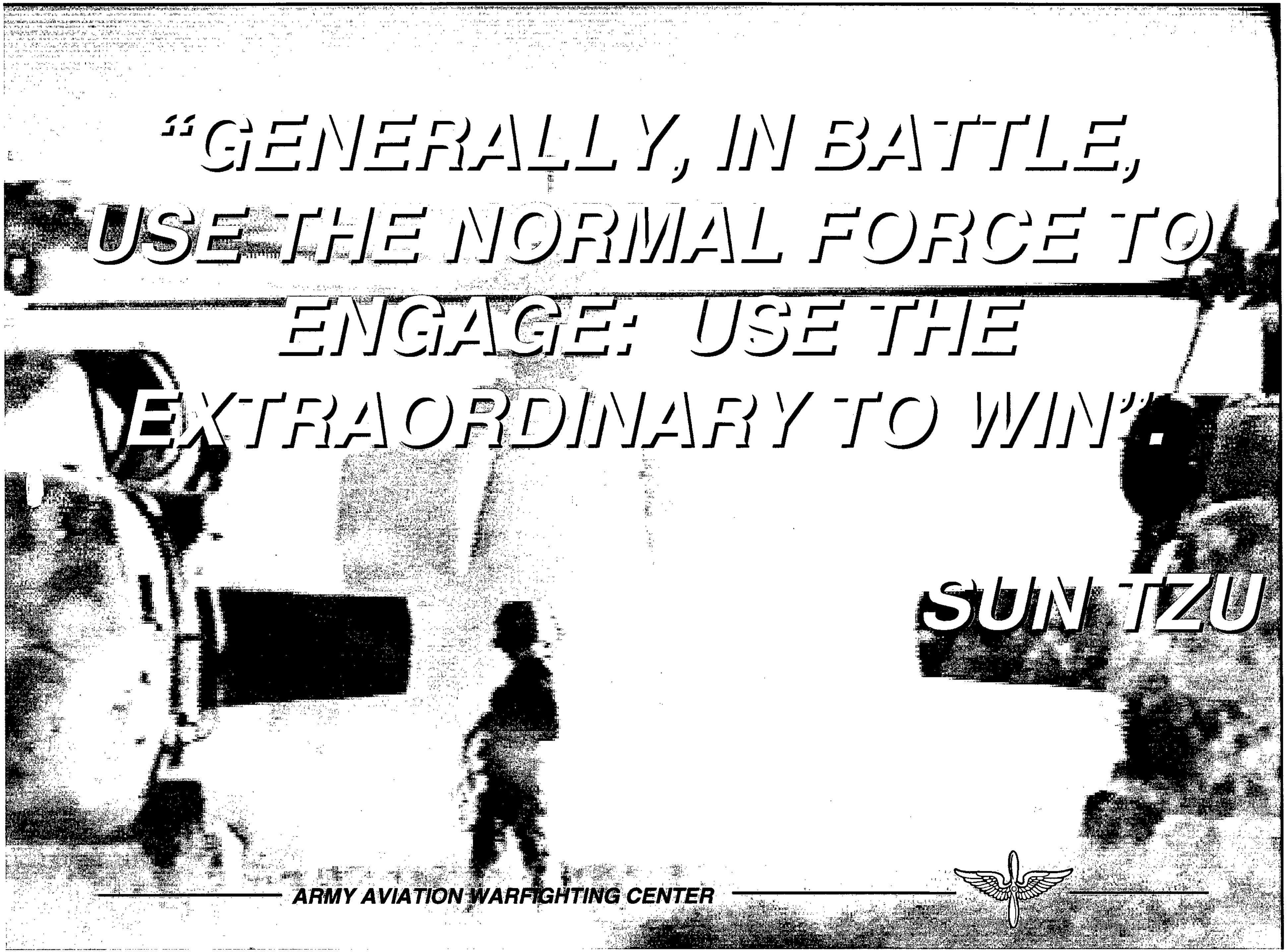


ARMY AVIATION WARFIGHTING CENTER

Summary

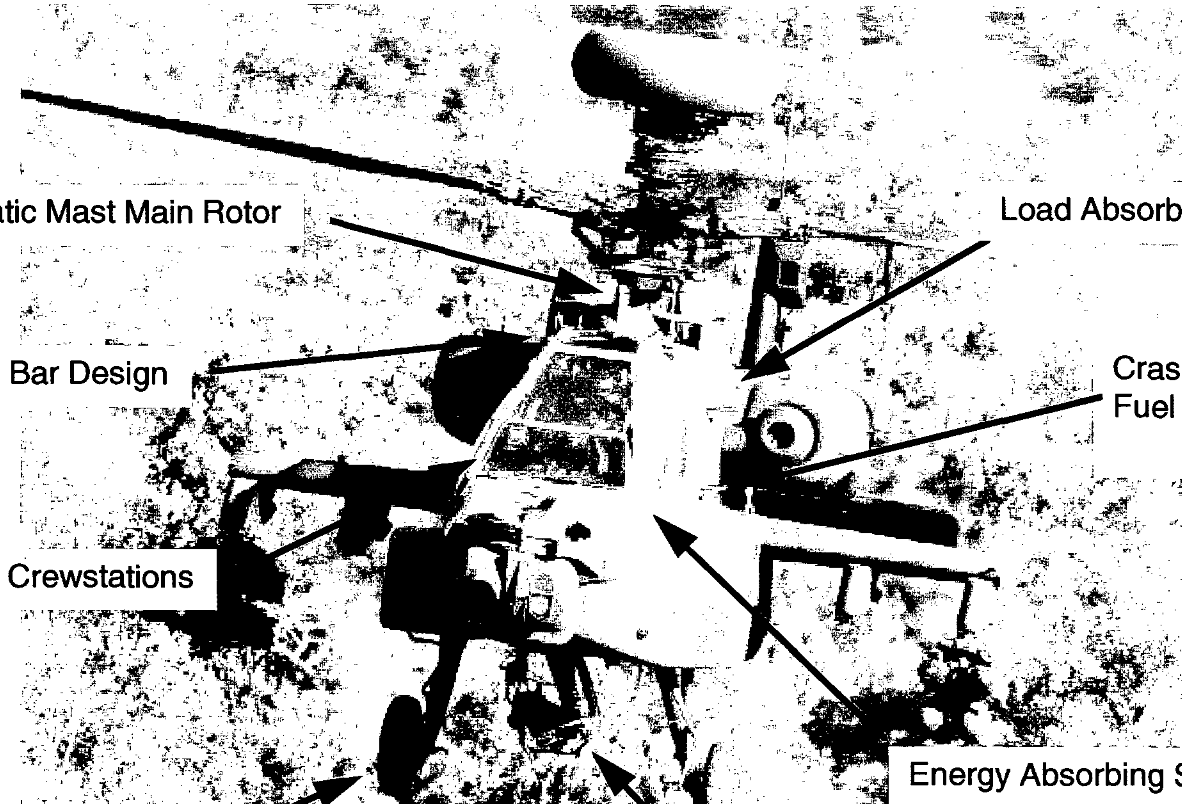
Chain of Survivability

- Avoid Detection
- Avoid Acquisition
- Avoid Damage
- Avoid Being Hit
- Protect the Crew


"GENERALLY, IN BATTLE, USE THE NORMAL FORCE TO ENGAGE: USE THE EXTRAORDINARY TO WIN".
SUN TZU
ARMY AVIATION WARFIGHTING CENTER

BACK-UPS

AH-64D Crashworthiness



Tactics, Techniques and Procedures

Terrain flight
Standoff
Night fighting
Digital communications for target handover
Rapid target acquisition and prioritization
Fire-and-forget

Fire Control Radar
- Adverse weather/obscurants
- Automatic multitarget:
  - Detection
  - Classification
  - Prioritization
- Terrain profiling
- Air targeting
- Moving and stationary targets

AGM-114L Longbow Hellfire Missile
- Fire-and forget
- Adverse weather/obscurants

Survivability Symposium

"Enhancing Aircraft Survivability - A Vulnerability Perspective"

Rear Admiral J. M. Johnson
Head, Aviation Plans and Requirements

Survivability Integration is Necessary to Obtain Optimal Solution

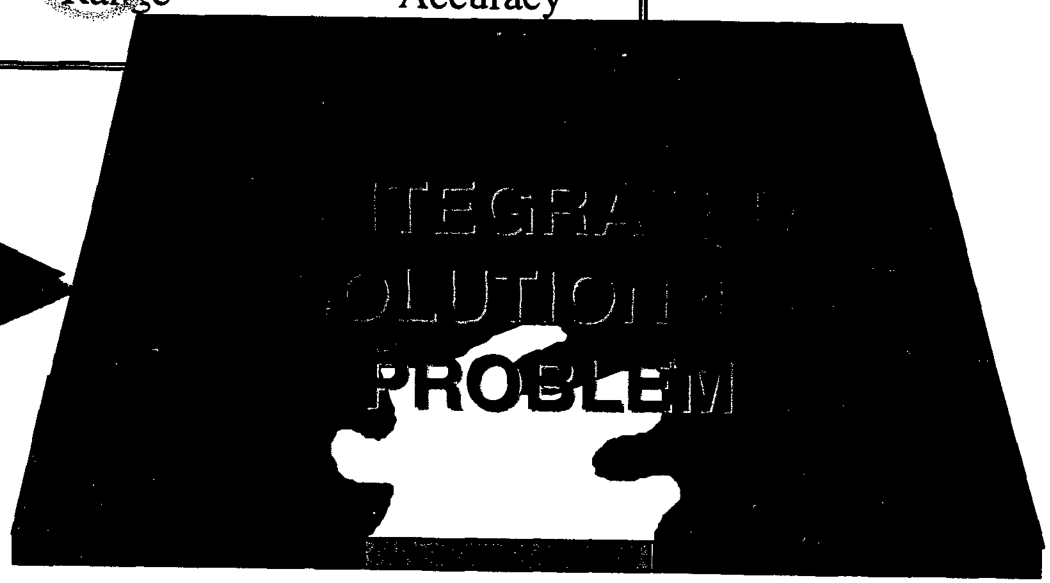
CUSTOMER PROBLEM TO SOLVE

MISSION CONTEXT

ELEMENTS OF SURVIVABILITY

THREAT	PLATFORM	WEAPON
• IR	• CM	• Payload
• RF	• Vulnerability	• Delivery
• EMP	• SIG	• Stand-off
• LASER	• Range	• Accuracy

SURVIVABILITY INTEGRATION (418000D)

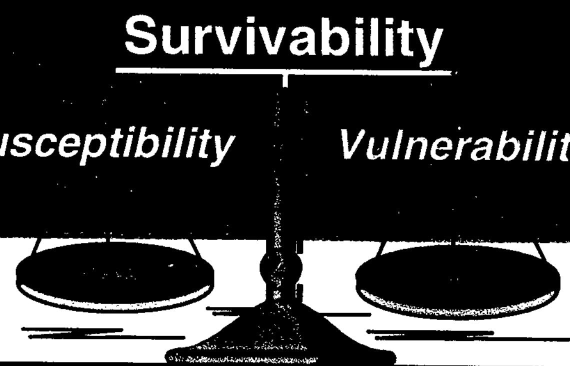


Survivability Today

Recognized As Design Discipline for Over 20 Years

- Still Means Different Things to Different People
  - Vulnerability Reduction -
  - Hardness - Armor
  - Defense Suppression
  - Countermeasures
  - Situation Awareness - Tactics - Speed
  - Stealth

It's all this and More
<u>But With Balance !</u>

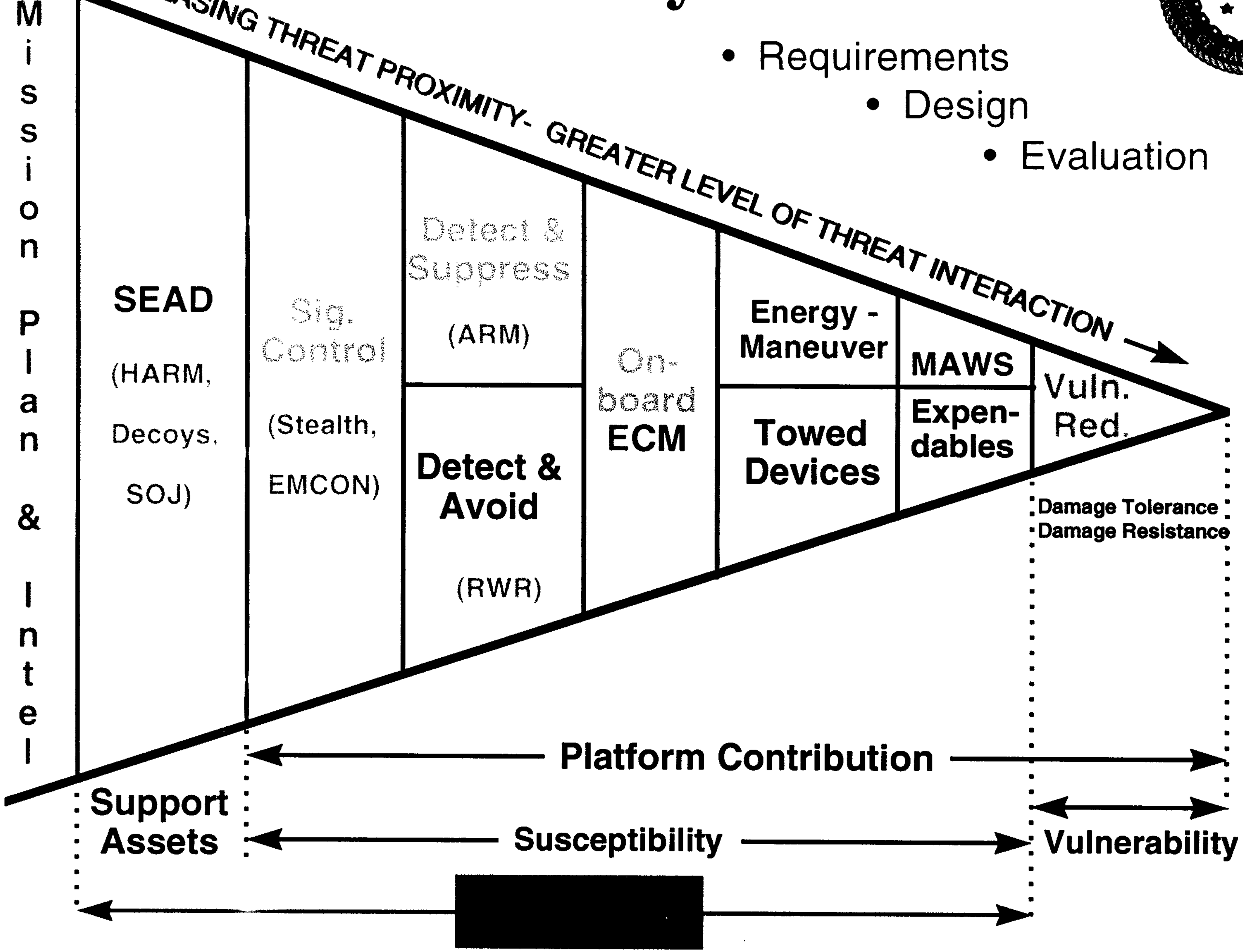


It a matter of System Engineering

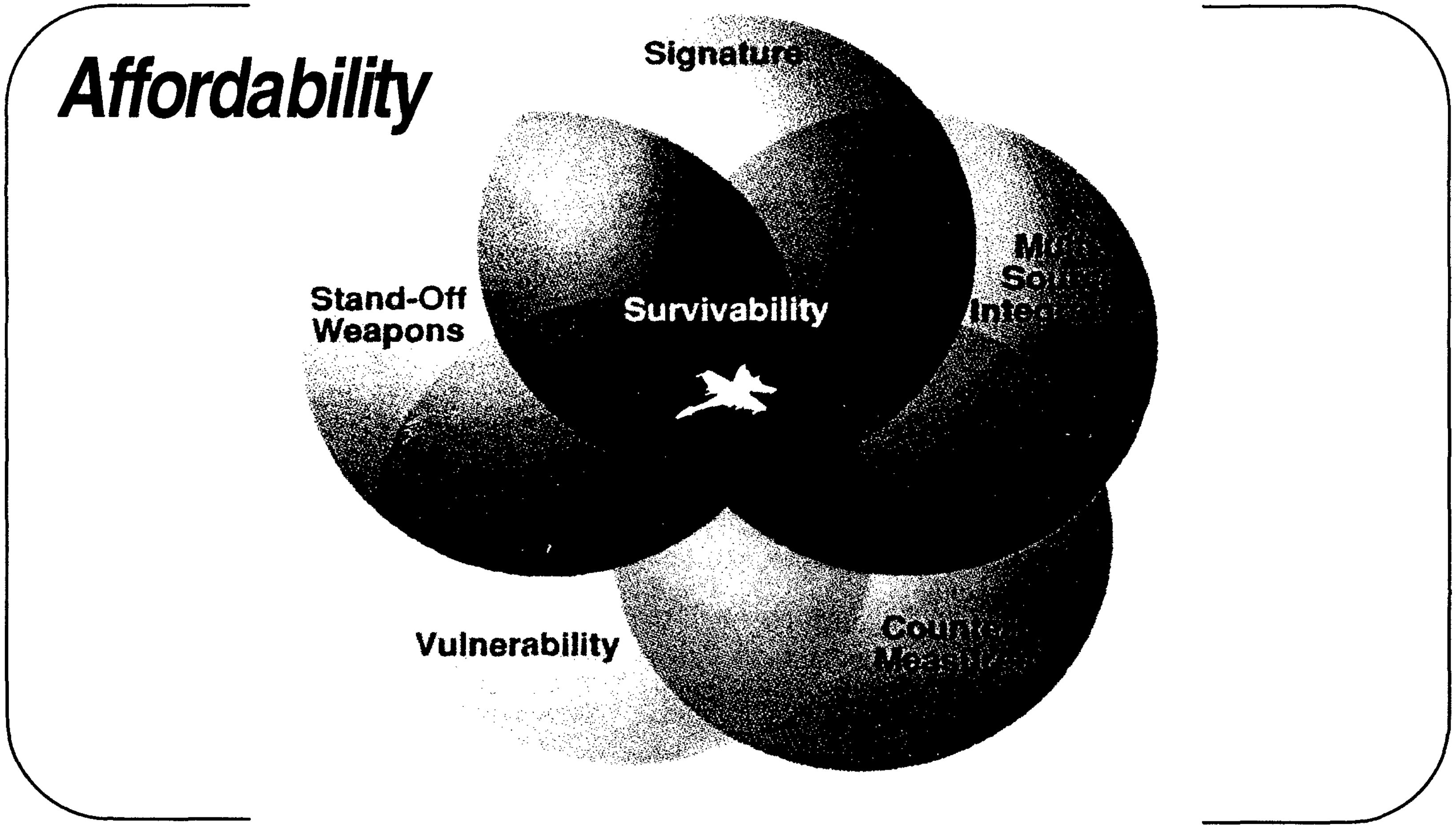
- Among the Susceptibility Reduction Features - LO, ECM, etc.
- Among the Vulnerability Reduction Features - Fire/Explosion, Robust Structures, etc.
- Contribution of Performance, Tactics
- Seek Best Survivability Across the Board, for Least Penalty
  - Weight; Cost; Supportability
- Measurable and Validated Through Assessments (Analysis & Test)

Survivability Assessment

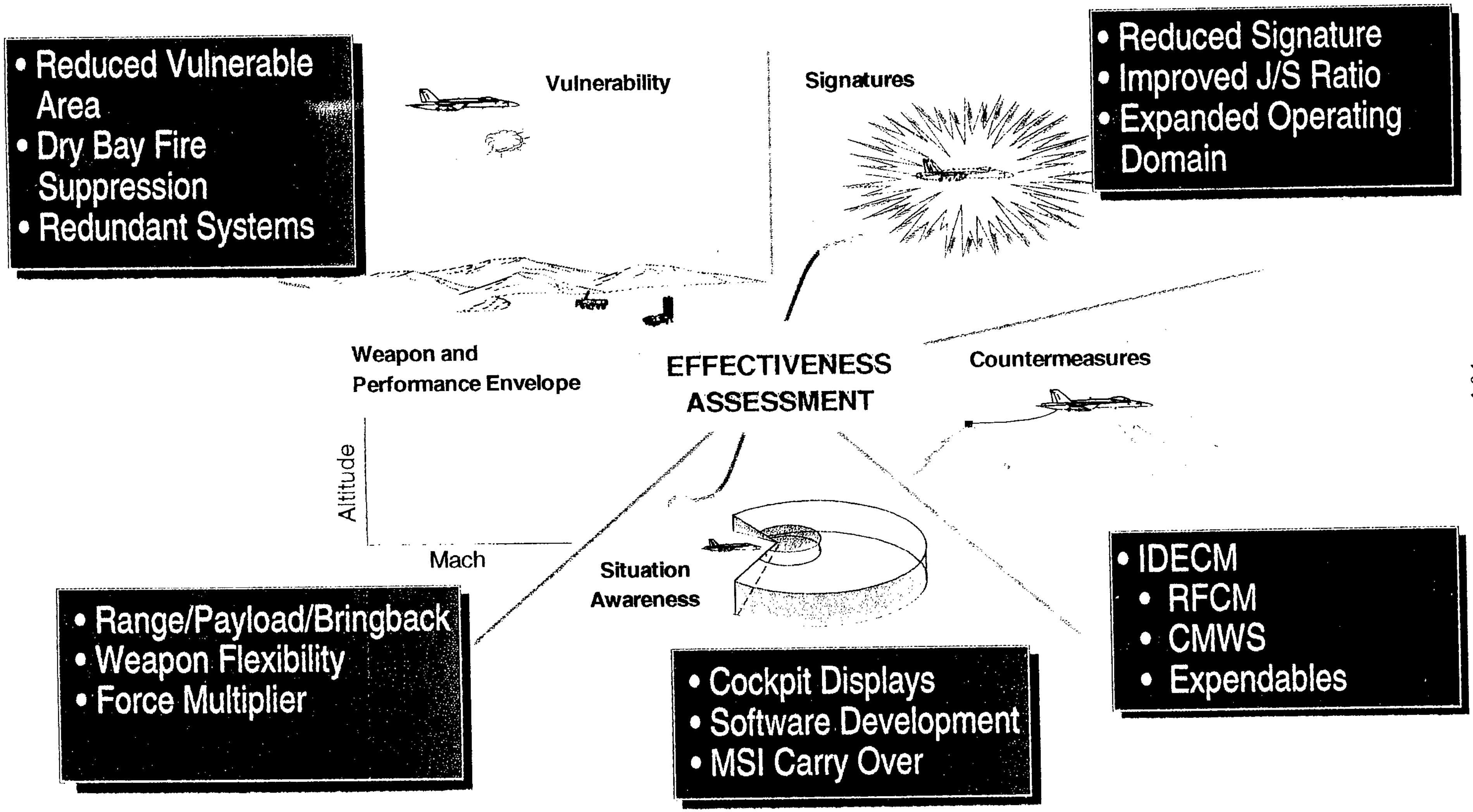
- Requirements
  - Design
    - Evaluation



F/A-18E/F
An Integrated Approach to Survivability

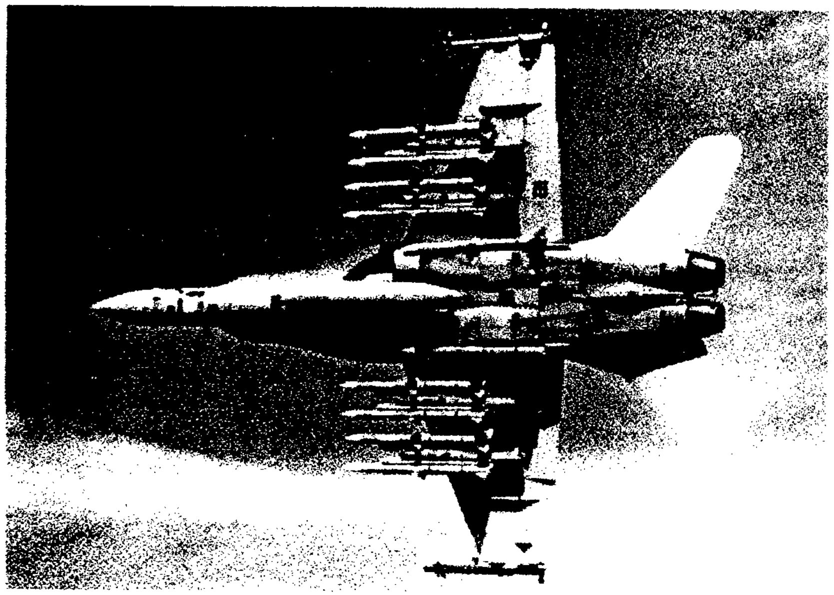


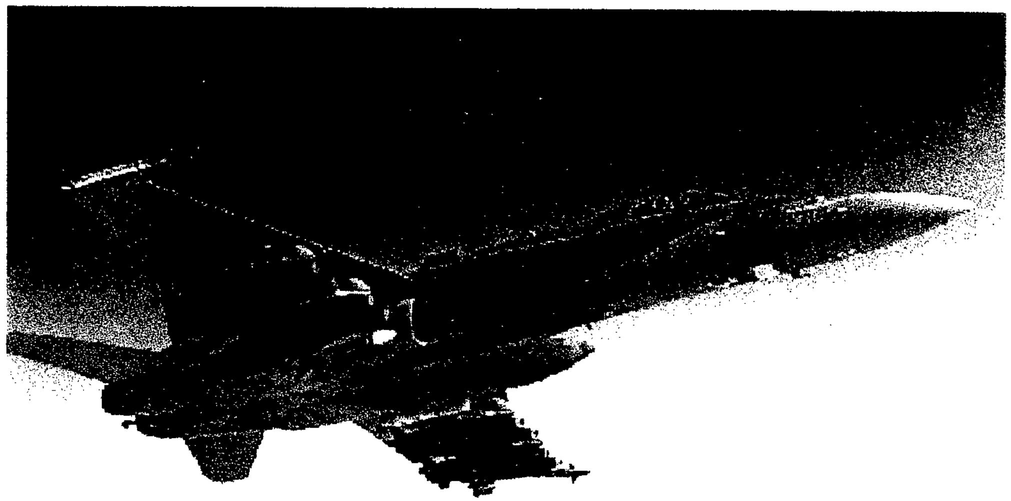
F/A-18E/F Survivability



Hornet Capability Spans the Mission Spectrum

F-14				F/A-18			A-6
Maritime Air Superiority	Air Combat Fighter	Recce	Fighter Escort	Close Air Support	Air Defense Suppression	Day/Night Strike	All Weather Attack





Perspectives on Operational Requirements and Vulnerability Reduction

ADPA Symposium, Naval Postgraduate School
October 21, 1997

Major General Fred McCorkle, USMC
CG, 3D MAW

With Apologies to the Schoolhouse......

-

- Susceptibility is an operational construct
  Vulnerability is a design and programmatic construct

Fiscal Realities

- In programmatic, material terms, Vulnerability reduction is a function of design and retrofit dollars available

Backdrop Assumptions

- The Marine Corps Aviation Combat Element (ACE) of the near term will be characterized by a "mature" assault support fleet of legacy aircraft that will still be operating 2010-2020

Backdrop Assumptions

- Threat proliferation trends will continue, with anti-aircraft weaponry expanding throughout the littoral battlespace
- Any weapon, anti-air or not, can kill USMC aircraft, given the right conditions
  - Waterfowl have at least 7 recorded kills

Backdrop Assumptions

- **The past, current, and future threats are ones which capitalize on some of our historical vulnerabilities:**
  - **IR hotspots**
  - **Aircrew safety**
  - **Intelligence gaps**
    Cultural Character (TRAP, NEO, etc)

Operational Realities

- The pace of technological change has far exceeded that of vulnerability reduction
  - The MV-22 of 2020 will continue to be vulnerable in some of the same ways as the CH-46 of 1965

Operational Realities (cont'd)

- Predicted operational tempos do not offer any relief from being exposed to increasing numbers of threats, especially in the urban environment

- For our present aircraft, vulnerability quotients will outpace reduction efforts as weapons become both more prevalent and accurate

Operational Perspective

- **Those factors which highlight present aircraft vulnerability are largely immutable:**
  - **Cannot select operating environment**
  - **Cannot preclude all weapon engagements**
  - **Cannot protect against every weapon**

  Multi-mission optimization has its costs...

Design and Programmatics

- **From the aspect of aircraft design and program management, actions which effect fleet aircraft vulnerability are addressable from this point <u>forward.</u>**
  <u>Retrofit is not a salable option</u>

Present Efforts

- **F/A-18 C/D Hornet**
  - Fuel System
    - Fuel isolation from engines
    - Fuel tank hydraulic ram
    - Self-sealing feed tanks and engine feed lines
    - Void filler foam for dry by fire protection below fuselage tanks
    - Wing tank unexpended fuel explosion protection
  - Flight Control System
    - Redundant separated hydraulics
    - Rip stop actuators, Hydraulic reservoir level sensing
    - Redundant flight control conputers
    - Mechanical backup
  - Propulsion System
    - Fire detection and extinguishing system
    - Blade containment measures
- **No improvements planned**

Present Efforts (cont'd)

- AV-8B (Day and Reman A/C)
  - No improvements planned
- EA-6B
  - Blk 89A Halon fire extinguisher
- KC-130F/R/T
  - No improvements planned

Present Efforts (cont'd)

- CH-46
  - Self-sealing fuel tanks
- No improvements planned
  CH-53D/E
  - Self-sealing fuel tanks
- No improvements planned
  UH-1N/4BN//AH-1W/4BW
  No improvements planned

Future Efforts

- **MV-22**
  - **Systems Protection**
    - **Armor**
    - **System Isolation**
    - **System Redundancy**
    - **System Separation**
  - **Ballistic tolerance**
    - **Engine Fire Suppression**
    - **Nitrogen Inerted Fuel Tanks**
    - **Self-sealing Fuel Bladders**
    - **Hydraulic Ram Protection**
    - **Dry Bay Fire Protection**
    - **Composite Structure**
    - **Capability vs. 23mm API (threshold = 12.7 mm)**

Future Efforts (cont'd)

- **KC-130J**
  - **Reticulated Wing Tank Foam**
    - **Approximately 80% improvement in vulnerability reduction**
  - **Data bus wiring**
    - **Reduces wiring bundling throughout aircraft**

Conclusion

- Future design goals make appropriate and overdue reductions in aircraft vulnerabilities
- Current aircraft will continue to present challenges for vulnerability reduction efforts

Backup slides
follow......

The Reality of USMC Operations

- Operational Maneuver from the Sea
- USMC must be "Ready on Arrival"
- The Battlespace may be Immature
- Close proximity to the threat
- Threats cover all spectra (RF, IR, Visual, Acoustic)

USMC Operations—Expeditionary

Immature Battlefield

- Intelligence capabilities not fully deployed
- Dominant battlefield knowledge not fully developed

Come as you are, Fight as you train

Expeditionary Operations

- Aircraft
  - Maintainable
  - Repairable
  - Small logistical tail
  - High sortie rate
    - minimum maintenance
  - Multi mission profile
- Mission
  - Dynamic, fluid threat
  - Proximity to threat
    - Min. reaction time
    - Low J/S strength
    - EOB inaccuracies
    - Exposure time
  - 24 hour operations
  - All spectrum threats

The Future

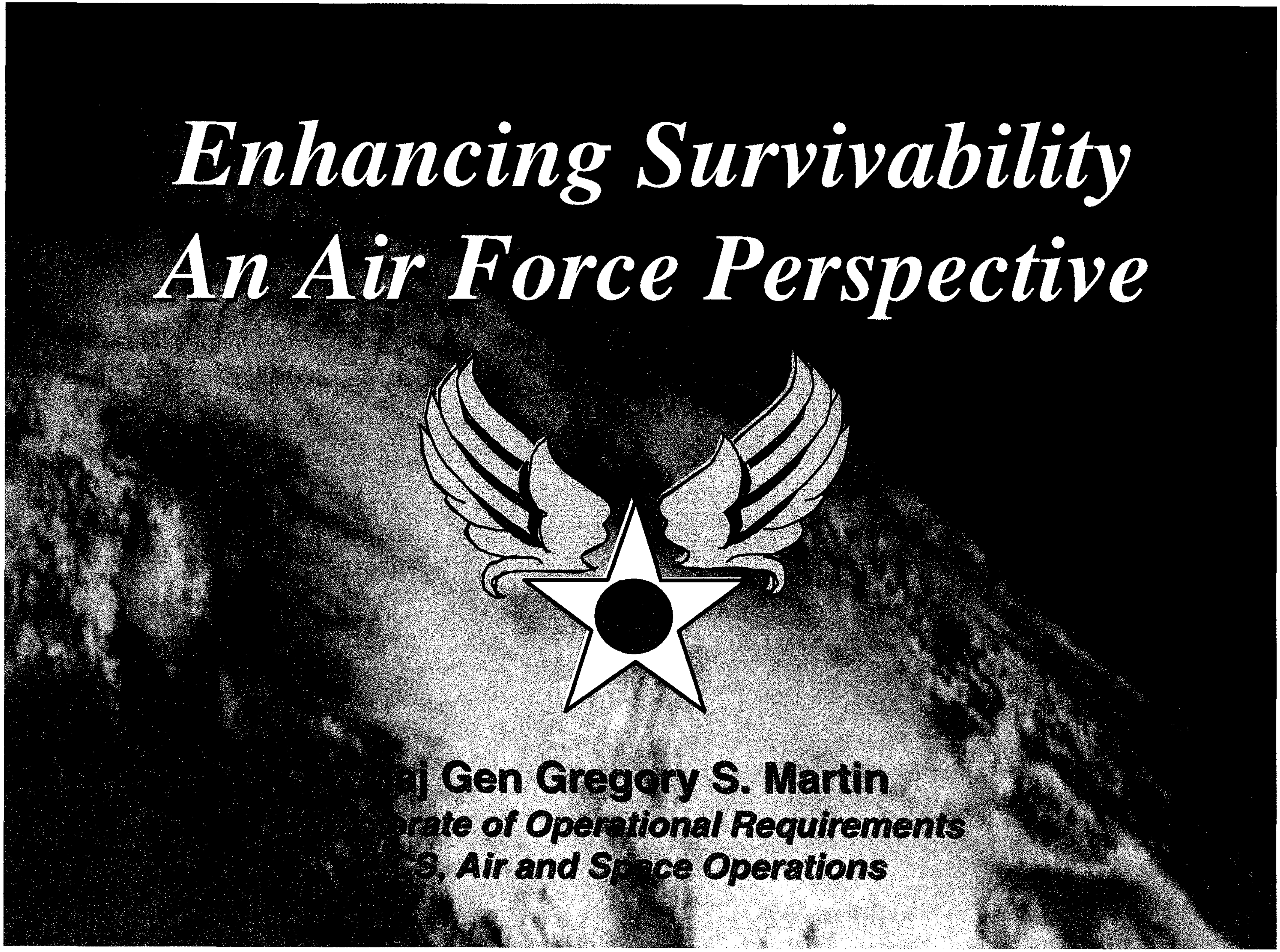
-
- Fixed Wing Attk — AV-8B+F-18C/D = JSF
  Support — EA-6B+C-130 = EA + C-
- 130J
- Rotary Wing Lift — CH-46+CH-53 = V-22
  Rotary Wing Attk — UH-1N+AH-1W = 4BN + 4BW =
  JRA

Force Mix Challenges Technology

Factors Affecting Investment Strategy

- Lack of independent resources
- Unique requirements
- Small force

Major Investments made by others


Enhancing Survivability
An Air Force Perspective
Gen Gregory S. Martin
of Operational Requirements
Air and Space Operations

Air Force Perspective

USAF

Enhancing Aircraft Survivability Requires a Prioritized Approach

- Eliminate enemy air defense systems
- Limit enemy engagement opportunities
- Self Protection

Offensive Posture Enhances Combat Effectiveness

Fundamental Lessons of Air Power

USAF

- **Air Superiority a Prerequisite for Success**

"If I didn't have Air Supremacy, I wouldn't be here"

-- Gen Eisenhower at Normandy

- **Pivotal in 20th Century Warfighting**

"Desert Storm taught us about air dominance. We had it, we liked it, and we're going to keep it"

-- Defense Secretary Perry

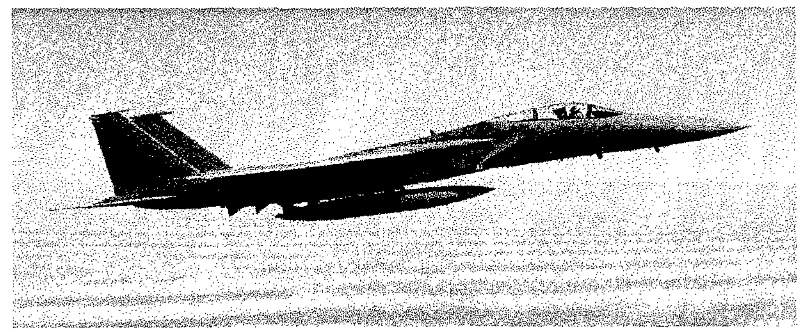
Fundamental Lessons Underscore Our Approach to Survivability -- Freedom from Attack Allows Freedom to Attack

USAF

Past Experience has shaped our Investment Strategy

Dominant Air Interceptor and Air Superiority Fighters


F-14


F-15

- Robust Avionics
  - Pulse Doppler Radars
  - Radar Warning Receivers
  - Electronic ID
- Highly Maneuverable
- Advanced Medium & Short Range A-A Weapons

Combined U.S. Kill Ratio of 38:0

... *Affordable and Versatile Multi-Role Platforms* ...

USAF

F-16

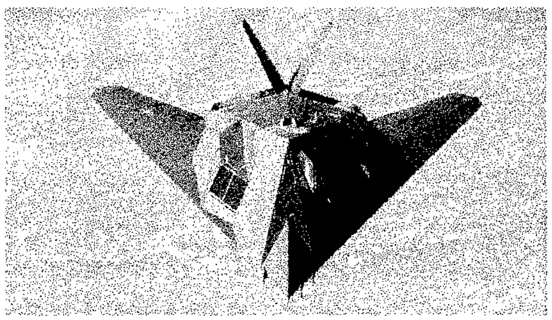
F-18

- **SEAD and PGM capable**
- **Balanced Investment in Avionics, Agility and Weapons**
- **Large numbers to Paralyze Enemy with Effective High Tempo Ops**

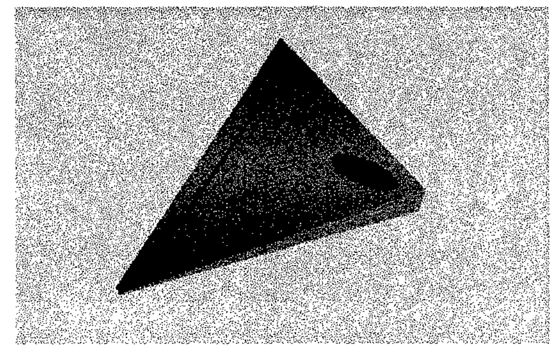
High Ops Tempo - - Constant Pressure - - Decisive Results

... *High Leverage Platforms*

USAF



F-117



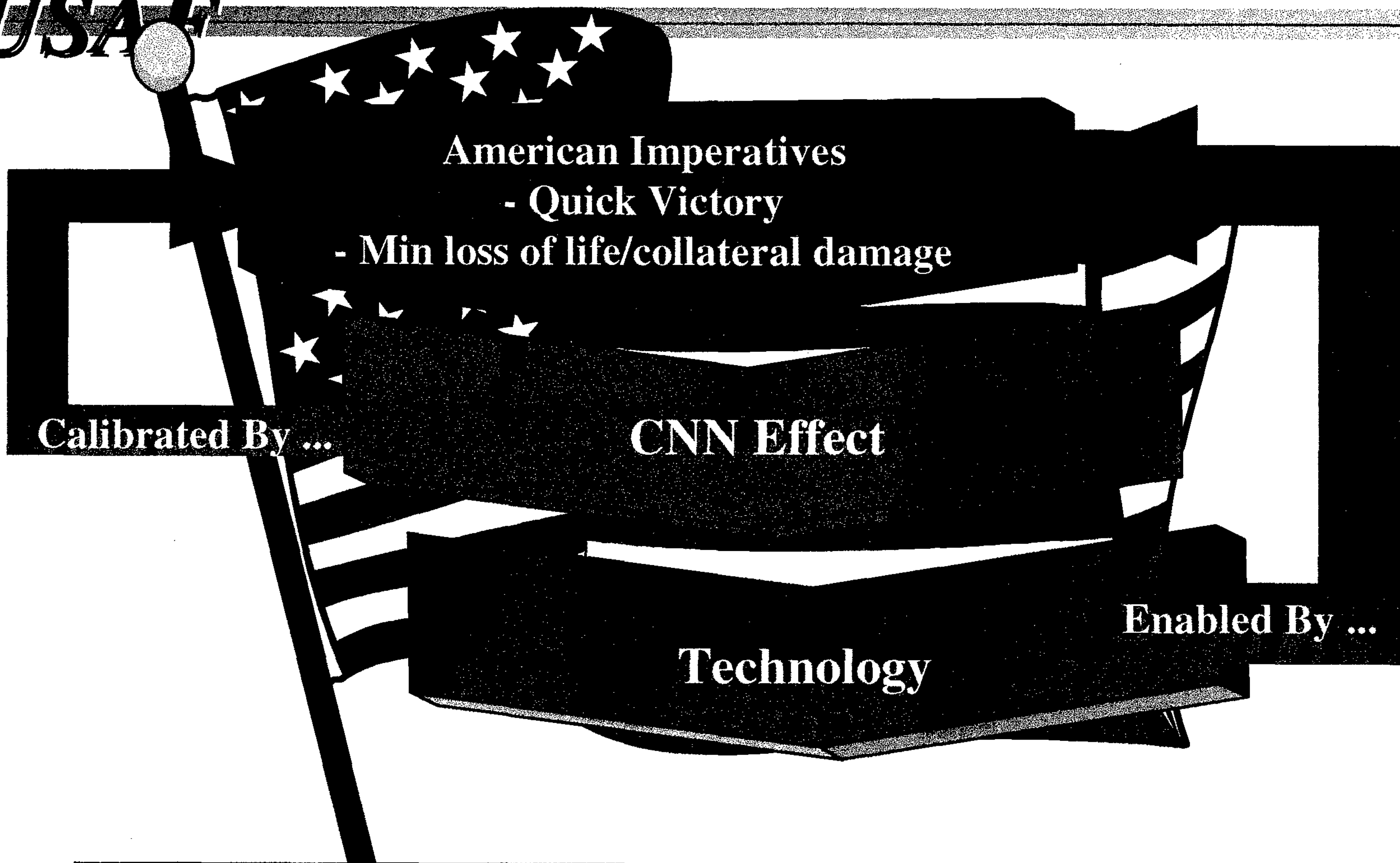
A-12

- **Capitalized on Stealth and PGMs**
- **Quantum leaps in survivability and lethality**

The New Calculus -- Not How Many Aircraft Per Target ...
But How Many Targets Per Aircraft

Our National Environment Demands Continued Improvement in Effectiveness ...

USAF



... Provides the Framework for JV2010 and Dictates Control of the Air as an Essential State

Air Dominance -- The Essential State

USAF

The Past **Now**

rity Parity Superio

What is Air Dominance?

- Quick ...

- Total ...

- All-Weather ...

- 24 hour a day...

... Control of the Entire Battlespace

Air Dominance - The Key to Reducing Total Force Vulnerability

Enabling and Leveraging Air Dominance

USAF

American Imperatives

Quick Victory

Minimal Casualties & Collateral Damage

-Rapidly mobile

-Quick control of battlespace

-Precision firepower

-Asymmetric force

- Parallel Attack

Air Power Attributes

Enabling Technologies

- Stealth

- Precision

- Fused Information

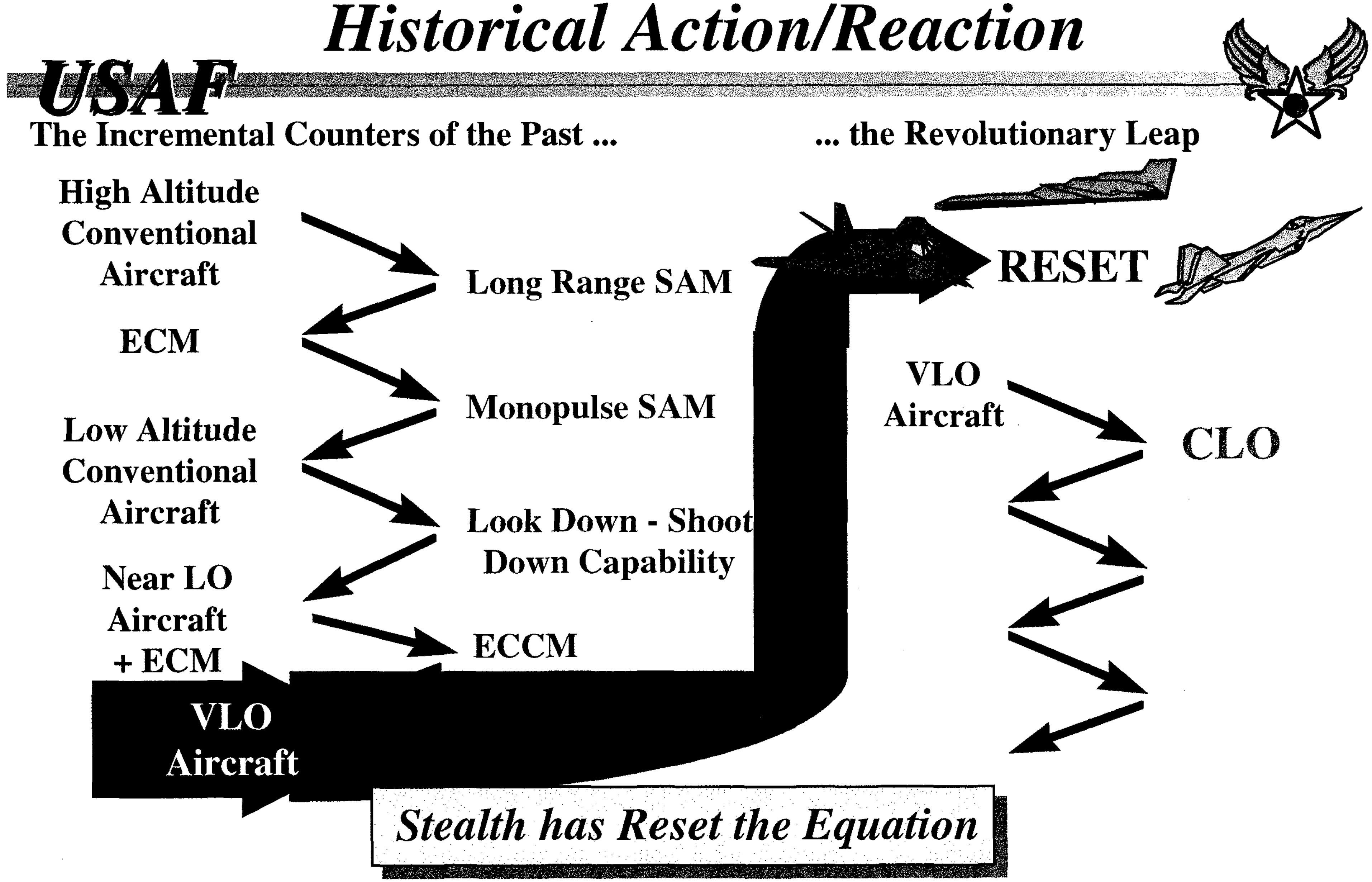
-Supportability

-Security from enemy attack

-Precise munitions and effects

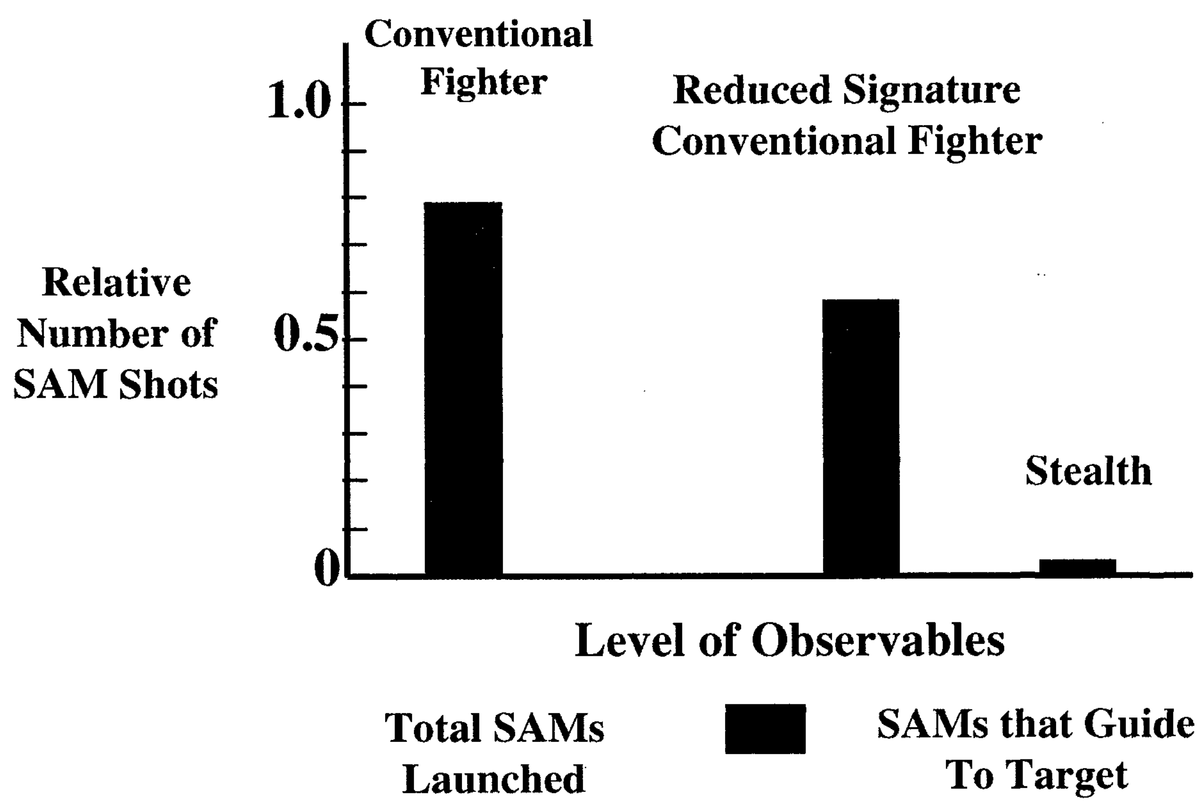
The Synergy of Enabling Technologies Provide the Best Path to Enhance Both Aircraft and Total Force Survivability

Stealth - A Revolutionary Counter to Historical Action/Reaction



Stealth's Contribution to Mission Effectiveness

USAF



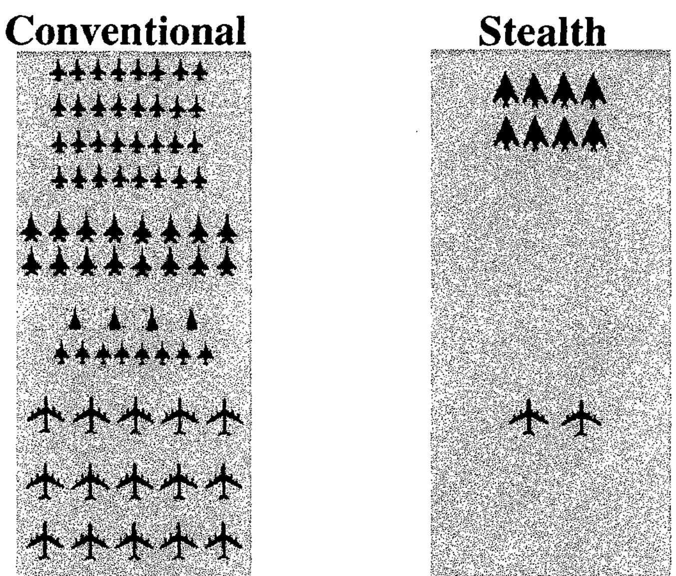
- **Stealth prevents a majority of the enemy's shot opportunities**
- **Conventional fighters must try to survive first**
- **Fighters cannot be *effective* when they are fighting for survival**

Stealth Provides an Effective, Survivable System

Stealth -- Combat Proven
Baghdad Nuclear Research Facility

USAF

First Attempt Second Attempt



First Attempt		Second Attempt
75	Aircraft	10
2	Aircraft Lost	0
0%	Success	100%

Leverage of Stealth

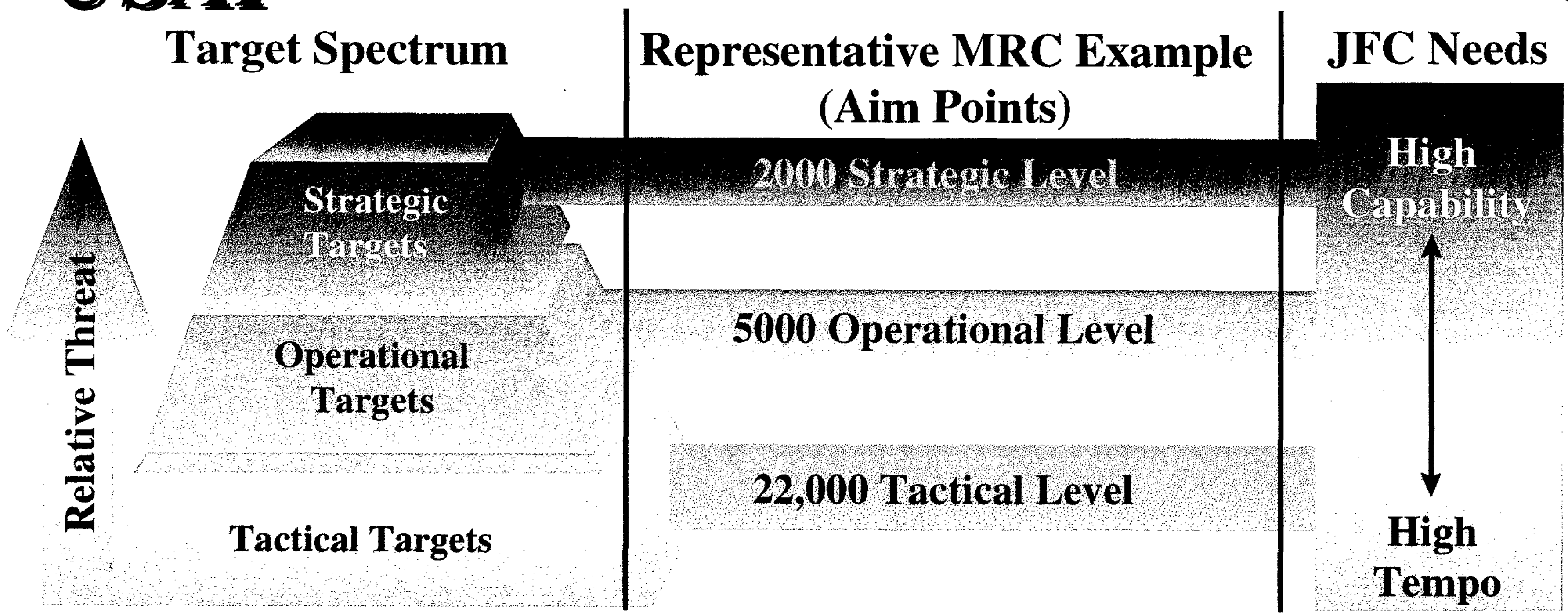
- 90% less aircrews at risk
  - Conventional package: 72-132
  - Stealth package: 8-16
- Value of assets at risk reduced by 74%
  - Conventional package: $2,328M
  - Stealth Package: $597M
- Time to initial capability cut in half/time to sustained capability cut by over 60%
  - Conventional package: 2.3 days to initial capability/5.2 days to sustained capability
  - Stealth package: 1.2 days to initial capability; 1.8 days to sustained capability

Stealth -- High Leverage Enabler for Most Challenging Targets -- Releases Bulk of Force for Other Priority Targets

SOURCE: USAF COST AND PLANNING FACTORS, AFI 65-503, CONSTANT 1994 DOLLARS

Level of Stealth is Driven by Aircraft Mission and Situational Threat

USAF



Strategic Targets: Leadership, NCA C3, Production Facilities, NBC, Elec power, TBM, Strat Defense
Operational Targets: Airfields/Shelters, Railroads/Bridges, Combat Support Nodes, Naval Ports, SAMs
Tactical Targets: Tanks, APCs, Artillery, Aircraft/helos in open, Ships and Vessels

JFC Requires Balance of Dominant Capability and High Operations Tempo to Service the Full-Spectrum of Targets

Precision -- Redefining Effectiveness While Minimizing Risk

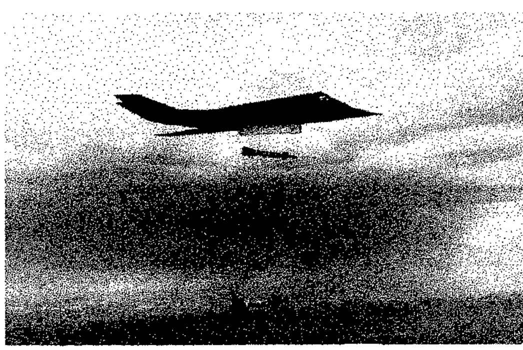
USAF

The Effort

- 1000 Plane Raids for one Target
- Multi-Year Efforts
- Large Number of Casualties
- Mass Destruction and Collateral Damage

World War

The Results



- Single Aircraft for Multiple Targets
- Maximum Effect with Minimal Collateral Damage at Risk

Gulf War

Precision Effectiveness -- During Gulf War, more targets were attacked in 24 hours than 8th AF attacked in all of 1942 and 1943

Information Fusion

USAF

Goal: Turn the "Fog of War" Into a Transparent Battlespace for the Warfighter

- **Enhancing Situational Awareness Critical to Improved Survivability**
  - SA-enhancing Radar Warning Receivers enabled an 80% reduction in enemy SAM effectiveness in Vietnam
    - -- Allowed the effective employment of ECM/SEAD
  - Survival in air-to-air combat hinges on high situational awareness
    - -- 80-90% of all losses in air-to-air combat were <u>unobserved</u> attacks
- **Information Critical for Mission Success**
  - Nodal Targing enabled by near-real time information in Bosnia -- Directly Responsible for the Resumption of the Dayton Peace Talks

Fused Information provides a Transparent Battlespace -- Improves Situational Awareness and Enables Rapid Exploitation

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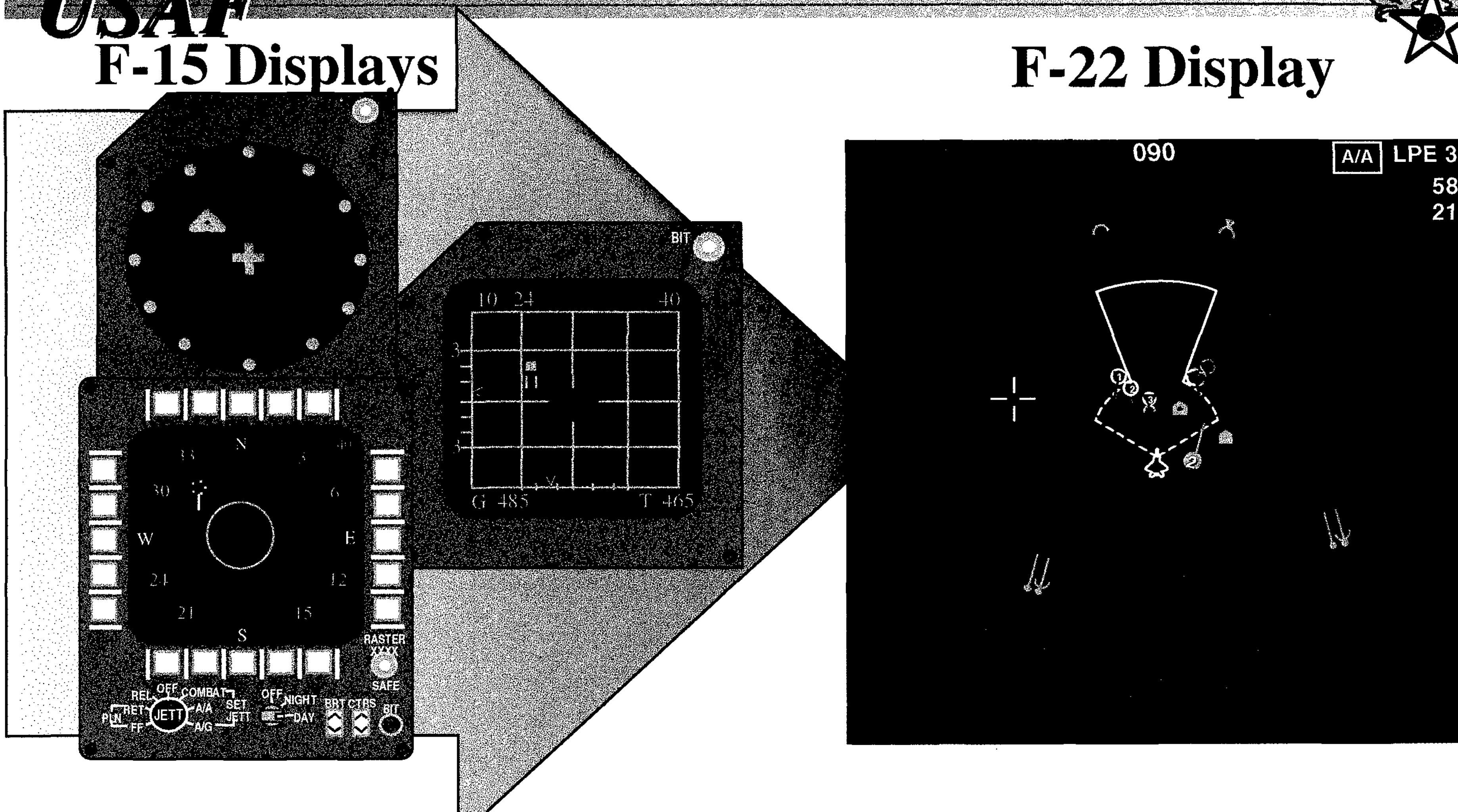
Fused Information -- Delivering Unprecedented Situational Awareness

USAF

F-15 Displays

F-22 Display



Pilot is Battle Manager vs Sensor Integrator

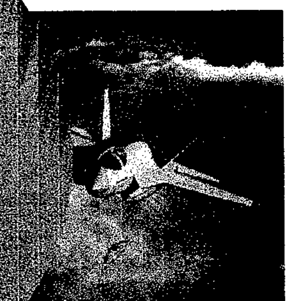
Fused Information -- Enabling Unprecedented Responsiveness

USAF

Sensor

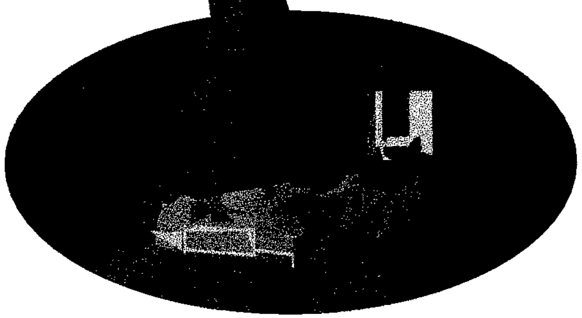
... and Near Real Time Information Transfer ...

Shooter



... Coupled with aircraft capable of operating effectivel within the enemy's airspace ...

Rapid tection and ID ...



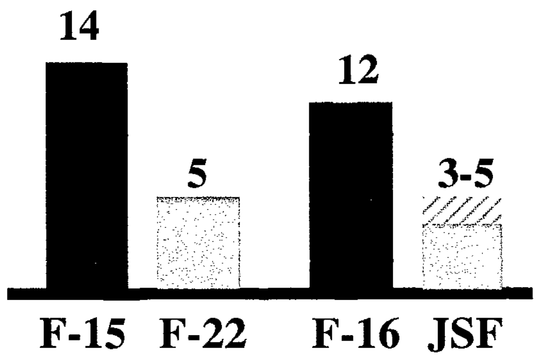
Result

... Reduces Detection to Destruction from Hours to Minutes

Supportability - Rapid Response, Operations Tempo, and Risk

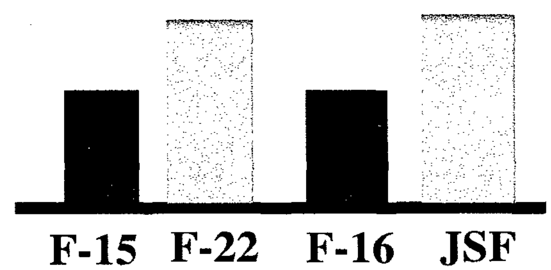
USAF

C-17s Required to Move a Squadron



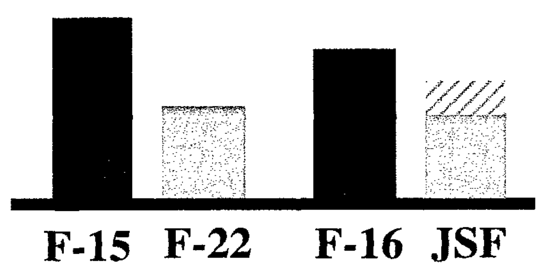
60-75% Reduction in Airlift Required

Relative Combat Sortie Rate



Approximately 50% Increase in Tempo

Support Personnel Required

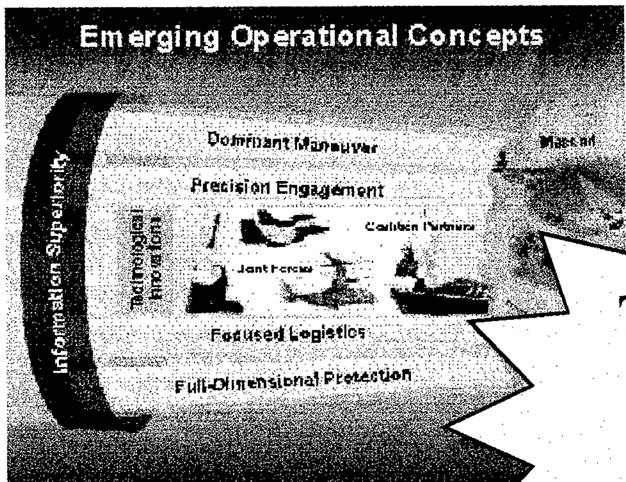


Approximately 20 - 40% Less Warriors at Risk

The Synergy of Enabling Technologies Answers Challenges to JV2010

USAF

The Vision



The Challenges ...

Theater Ballistic Missiles

Cruise Missiles

Advanced Fighters

o-Air
siles

Enabling Technologies

- Stealth

- Precision

- Fused Information

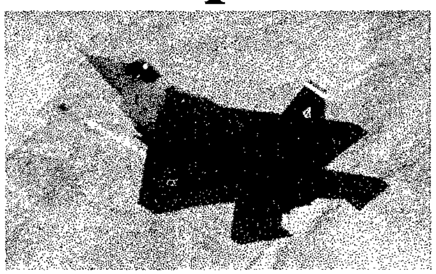
-Supportability

The Payoffs ...

The Freedom From Attack . . .

USAF

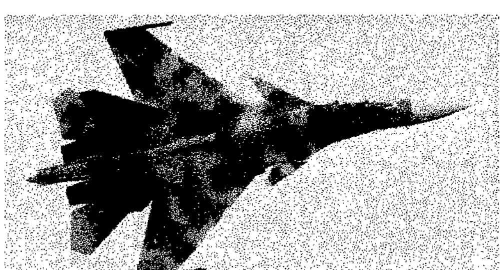
Compared to Legacy Force, our 21st Century Force ...



. . . Seizes Control of the Air in Less than Half the Time

. . . Reduces Unintercepted TBMs by 47%

-- Attack Operations and Airborne Laser more effective

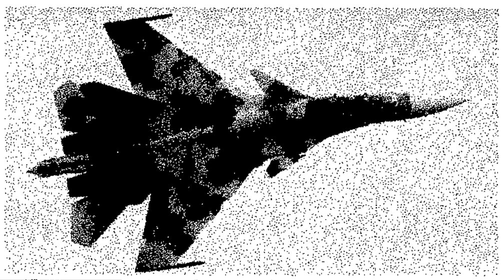


. . . Reduces Enemy Offensive Sorties by 45%

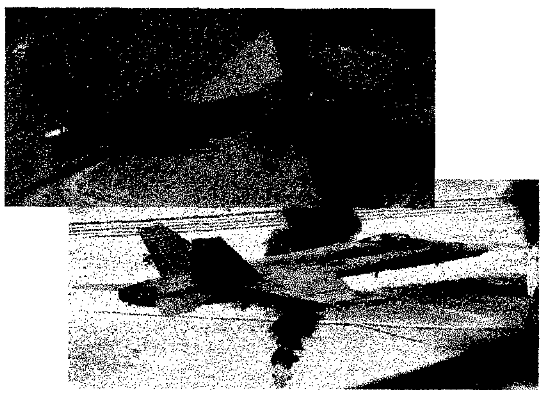
. . . *the Freedom To Attack* ...

USAF

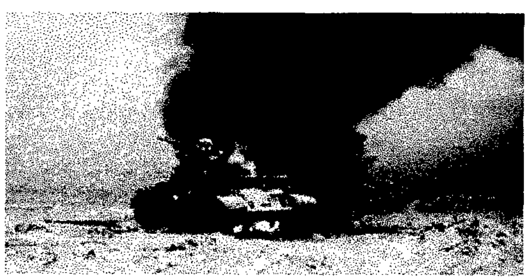
Compared to Legacy Force, our 21st Century Force ...



. . . Reduces Enemy Defensive Sorties by 48%



. . . Reduces Friendly Air Losses by 50%

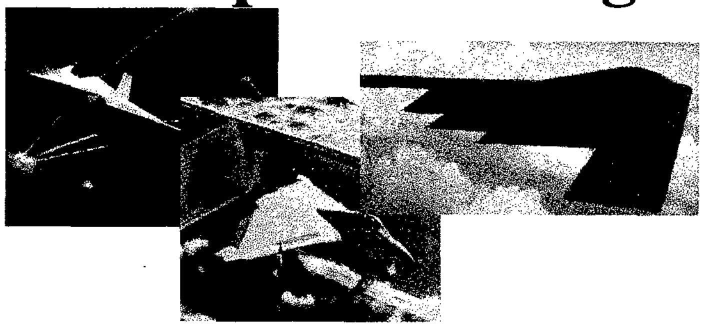


. . . Increases Friendly Kills of Enemy Equipment

... *and Enables an Early Halt*

USAF

Compared to Legacy Force, our 21st Century Force ...



. . . Halts Invasion in Half the Time

. . . Destroys 50% More Enemy Equipment

. . . Reduces Enemy WMD Facilities by an additional 76%

This Approach Reduces Total Force Risk

USAF

- **The Operational Concepts of JV2010 depend on Air Dominance**

- **Air Dominance enabled by:**

Enabling Technologies
- Stealth
- Precision
- Fused Information
-Supportability

Increased Survivability

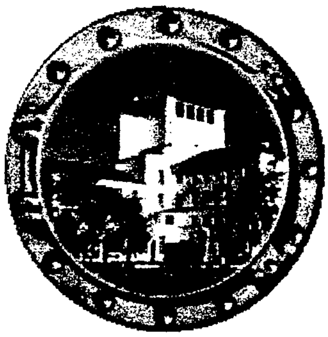
Result...

Rapid Response, Early Halt, and Decisive Victory
...With Minimal Loss of Life and Collateral Damage

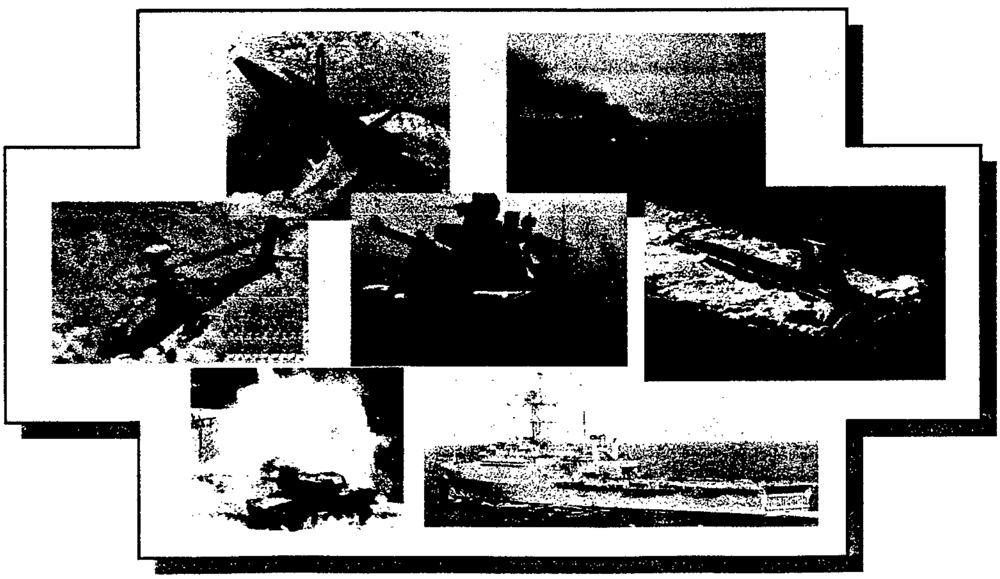
Aircraft Survivability:
A Look into the Crystal Ball
(A Composite Sketch)

October 21, 1997

To:



James F. O'Bryon
Deputy Director
Operational Test and Evaluation
Office of the Secretary of Defense
Room 1C730, Pentagon
(703) 614-5408
E-Mail: jobryon@dote.osd.mil



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Equal Factors

"Many factors influence aircraft survivability. Detection and tracking, susceptibility, performance and agility, and types of weapons used.

All play a role, as do an aviator's skills and the effectiveness of his tactics. But even if all our susceptibility reduction techniques work perfectly, **the odds are we will still take some hits.**

Therefore, **minimizing physical vulnerability is an equally important factor** in the overall survivability equation."

Rear Admiral John F. Calvert
PEO Tactical A/C
Navy Assistant Secretary, RDA
A/C Survivability magazine
September 1990, p. 6

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Misperceptions About Aircraft Survivability

1. Reducing aircraft vulnerability always has significant weight penalties.

2. Susceptibility reduction does not constitute the addition of significant weight.

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Misperceptions About Aircraft Vulnerability
(continued)

3. Vulnerability reduction and susceptibility reduction are mutually exclusive.

4. Aircraft always will be flying when subjected to threats.

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Misperceptions About Aircraft Vulnerability
(continued)

5. We won't get hit.

6. Vulnerability reduction applies only to damage caused by combat.

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Misperceptions About Aircraft Vulnerability
(continued)

7. There is no need to quantify vulnerability is one sufficiently can quantify susceptibility.

8. An aircraft hit is an aircraft killed.

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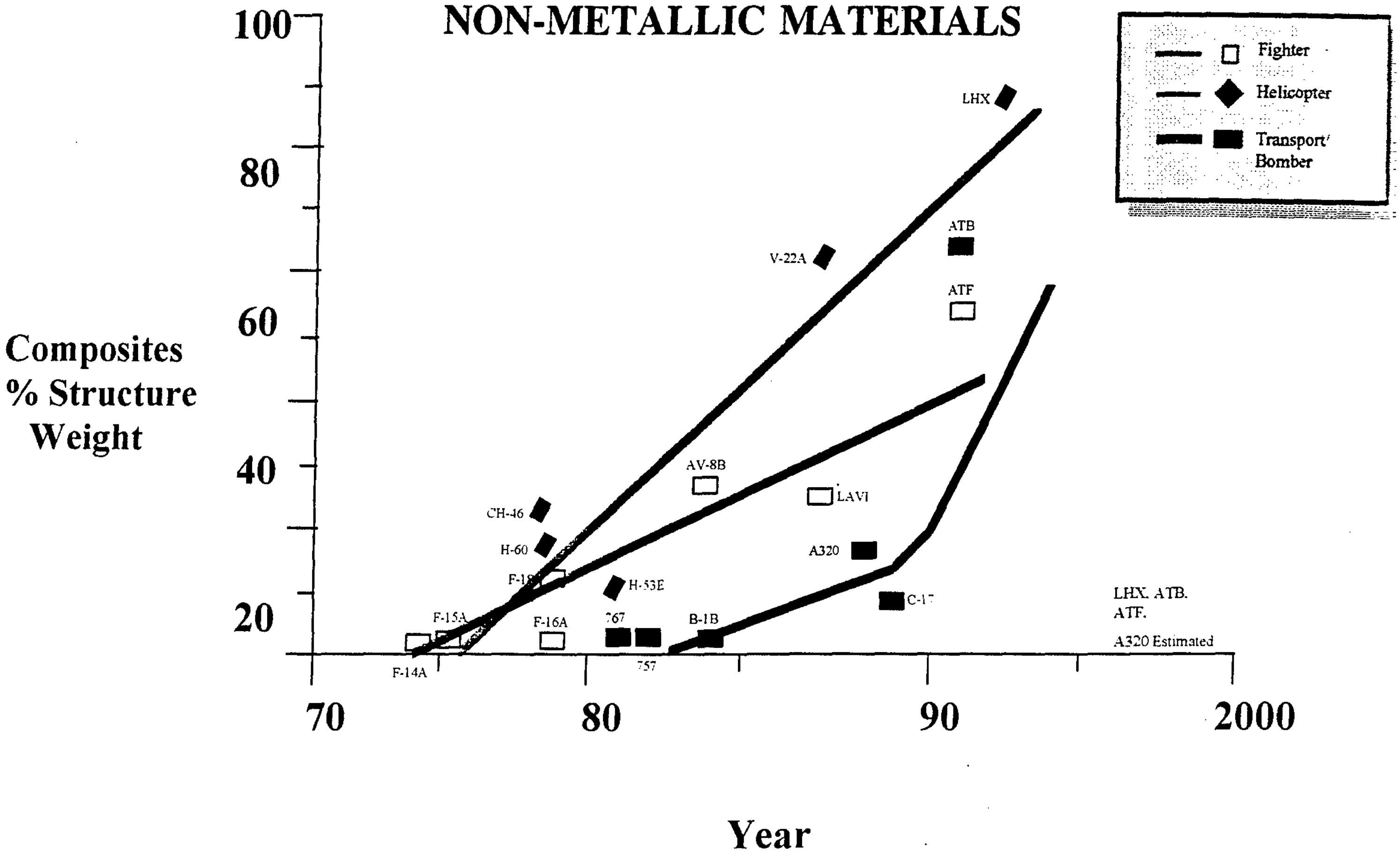
10 TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

GROWING USE OF NON-METALLIC MATERIALS

- O INADEQUATE DATA BASE
- O DANGERS OF EXTRAPOLATION FROM METALLIC DATA BASE AND FROM LOW VELOCITY IMPACTS ON COMPOSITES
- O DIFFICULTIES IN DIAGNOSING VULNERABILITY (E.G. DELAMINATION)
- O ADDED COST OF MANUFACTURE
- O ADDED COST OF MAINTENANCE
- O ADDED SUSCEPTIBILITY TO RF AND LIGHTNING DAMAGE

GROWING DEPENDENCE ON NON-METALLIC MATERIALS



TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

INCREASING USE OF COST / BENEFIT

- O UNDER-ESTIMATION OF BENEFITS
- O VALUE OF HUMAN LIVES SAVED OFTEN NOT INCLUDED
- O NO EXISTING METHOD IS ABLE TO CAPTURE THE VERY REAL BUT NON-QUANTIFIABLE BENEFITS

Quantifying the Value of a Life

The Department of Transportation uses several methods:

1. Lifetime earning power lost to the family.

2. Economic loss to the organization from which the individual came.

3. Anticipated amount of money an insurance company would award if life was lost.

4. Punitive costs expected to be paid by an agency found at fault for loss of life.

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VULNERABILITY T&E PAYOFFS

INSIGHTS & FIXES YIELD NOT ONLY REDUCED ATTRITION IN COMBAT <u>ALSO YIELDS</u>

- O MORE DURABLE ROBUST A/C IN PEACETIME
- O LONGER A/C LIFESPAN
- O HIGHER TOLERANCE TO FOD, BIRDSTRIKES
- O HIGH TOLERANCE TO HARD LANDINGS
- O INSIGHTS WHICH CAN RESULT IN BETTER TACTICS (DIFFERENT COMBAT EXPOSURES)
- O DESIGN LESSONS FOR APPLICATION TO FUTURE AIRCRAFT
- O BATTLE DAMAGE AND REPAIR INSIGHTS, PRACTICE AND PROCEDURES
- O ADDED DISCIPLINE TO THE T&E PROCESS
- O DATA TO REVISE / CORRECT / CALIBRATE M&S TOOLS FOR BOTH FUTURE DESIGNS & DIAGNOSTICS & BETTER DIAGNOSTIC TOOLS FOR ASSESSMENT OF PAST A/C FAILURES

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

GROWING RELIANCE ON STEALTH

- O LESS TRADE SPACE LEFT FOR VULNERABILITY REDUCTION
- O MANY STEALTH MATERIALS NOT OPTIMIZED FOR STRENGTH
- O ADDED WEIGHT TO ACHIEVE LO
- O POTENTIAL TECHNOLOGICAL BREAKTHROUGHS IN TARGET ACQUISITION COULD NEGATE STEALTH
- O LITTLE TO NO PAYOFF IN PEACETIME
- O HEAVY MAINTENANCE BURDEN
- O SMALL HITS - LARGE RCS GROWTH
- o COSTLY INVESTMENTS IN STEALTH LEAVING LESS $ LEFT FOR VULNERABILITY REDUCTION TRADES

Stealth
According to Kasich
(continued)

- Stealth is not invulnerability or invisibility. It is management of the aircraft's signature.

- Just as there is no "free lunch," Stealth is a compromise.

- The stealthier an aircraft, the more likely it is to degrade other desirable combat characteristics, such as speed, maneuverability or payload.

- Stealth is inherently expensive and difficult to maintain; the coating degrades with each mission. Stealth is not an all aspect cloak of invisibility. It is optimized to defeat radars ahead of the aircraft, but is less effective from other angles."

John R. Kasich
Washington Post
July 19, 1995

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Stealth According to Kasich
(continued)

Historically, weight growth/cost growth has been attributed unjustifiably to primarily vulnerability reduction.

"The risk/benefit trade space for stealth also has very significant procurement cost, weight, performance and maintenance penalties, which must be integral to any cost/benefit study."

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

GROWTH OF "PEACETIME VULNERABILITY" LOSSES

- O BIRD STRIKES
- O LIGHTNING STRIKES
- O WIRE STRIKES
- O FOD
- O TRAINING ACCIDENTS

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

HEAVIER RELIANCE ON MANEUVER

- O GROWING G-LOADING (BOTH + AND -) ON AIRFRAME
- O GROWING G-LOADING (BOTH + AND -) ON PILOT(S) (GLOC / ALOC IMPLICATIONS)

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

CHANGING NATURE OF THE THREAT

- O NOT JUST BIGGER, BETTER, FASTER
- O FROM BULLETS TO SMART BULLETS
- O FROM MISSILES TO SMART MISSILES
- O FROM BALLISTIC TOWARD DIRECTED ENERGY
- O EMERGENCE OF "NICHE WARFARE"
- O SOFT KILLS BECOMING AS CRITICAL AS HARD KILLS

Scope of LFT&E Threat Considerations

Some Ballistic Threat Types	Some Non-ballistic Threat Types	Non-LFT Threat Types
Small Arms	Lasers	Nuclear
Fragmenting Projectiles	Incendiaries	Thermonuclear
Shaped Charges	Blast/Fuel Air Explosives	Chemical
Kinetic Energy Rods	Charged Particle Beams	Biological
Self-Forging Frag	High Powered Microwaves	
High Explosives		

← Traditional → ← Non-Traditional →

← Conventional → ← Unconventional →

← Covered By Live Fire Requirements → ← Not Covered →

Future Trends in LFT&E

* New systems are becoming more complex:

Computer-based + Light weight

=

Easier shock kills

---

* Testing needs to rethink what it is trying to find out:

Live Fire Test design must account for the "soft" kills
and
partial kills
not Live Fire and Brimstone

Live Fire Testing

≠

Live Fire & Brimstone Testing

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

TREND TOWARD MORE INTERNALLY STOWED MUNITIONS

- O INCREASES STEALTH AND RANGE
- O SIGNIFICANTLY INCREASES A/C VULNERABILITY
- O A/C MUST BE TREATED AS TOTAL SYSTEM - INCLUDING STOWED MUNITIONS

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

HEAVIER RELIANCE ON M&S

- O MODELS STILL INADEQUATE TO PREDICT VULNERABILITY, AT THE COMPONENT LEVEL, LET ALONE AT THE FULL-UP SYSTEM-LEVEL

- O INADEQUATE ARCHITECTURES TO YIELD MEASURABLE AND COMPARABLE OUTPUT METRICS

- O SOME PHENOMENA NOT MODELED ADEQUATELY OR AT ALL (FOLLOW-THROUGH FIRE, ULLAGE, HYRDO RAM, SPALL, RICOCHET, RF. ETC)

DOT&E/LFT&E SUPPORT TO M&S

1. LFT&E / JLF

o SHORTER TERM
o WEAPON / PLATFORM SPECIFIC
o TEST DRIVEN w/ PRE-SHOT PREDICTIONS
o PRIMARILY FROM EMPIRICALLY BASED MODELS

2. TILV

o MID-TERM
o MORE TARGET GENERIC (A/C, SHIPS, COMBAT VEHICLES)
o TEST & MODEL DRIVEN

3. DOT&E/LFT&E / DOE ASCI MOA

o LONGER TERM
o MOST TARGET INDEPENDENT
o "PHYSICS-BASED MODELS" VALIDATED BY REALISTIC LFT&E TEST OPPORTUNITIES

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

MOVE TOWARD COMMERCIAL SPECS AND STANDARDS

- O LESSONS BEHIND EXTANT MILSPECS NOT OFTEN AVAILABLE OR HEEDED
- O POTENTIAL LIABILITY TO A/C MANUFACTURERS IF ATTRIBUTABLE LOSS OF A/C AND/OR LIFE TO "POOR" DESIGN
- O PEACETIME MENTALITY PERVADING A/C MINDSET

TRENDS AND CONCERNS IMPACTING THE AIRCRAFT SURVIVABILITY COMMUNITY

MOVE TOWARD MARGINALLY STABLE / AERODYNAMICALLY UNSTABLE AIRCRAFT

- O IMPACT OF DAMAGE TO CONTROL SURFACES
- O EFFECT OF DAMAGE / DEGRADATION TO FLIGHT CONTROLS & SOFTWARE, POSSIBLE LOSS OF CONTROL
- O AI IMPLICATIONS

Objectives of LFT&E

- To enable the Secretary to make informed system acquisition decisions

- To gain insights into potential design flaws so that they can be corrected before entering full-rate production

- To ensure that knowledge of system survivability and lethality is based on realistic testing of the system configured for combat against expected threats

- Primary emphasis on testing vulnerability with respect to potential user casualties
  - Individual Soldiers
  - Armor Crews
  - Aircraft Crews
  - Ship Crews
  - Tactical Vehicle Crews

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NEW LFT&E AND TRAINING INITIATIVE (LFT&TI)

- O ADDRESSES SECDEF'S T&E THRUSTS
- O SUPPORT FROM CONGRESS INITIATED IN FY97 AND GROWING
- O TAKING LFT&E RESULTS, TESTS, OPPORTUNITIES, INSIGHTS AND PROVIDE THESE TO THE TRAINING COMMUNITY FOR THEIR BENEFIT
- O TAKING TRAINING OPPORTUNITIES TO GATHER FURTHER LFT&E INSIGHTS

LFT Payoffs

- **Provides the data necessary to make fully informed acquisition decisions**
- **Provides insights into vulnerability and/or lethality of systems in development**
- **Adds discipline to the test design process**
- **Provides battle damage and repair insights for training**
- **Provides spare parts stockage level data**
- **Teaches tactics lessons**
- **Feeds operational test assessment**
- **Provides necessary input to overall survivability analysis**
- **Provides basis for P_K's for force-on-force models (procurement mix)**
- **Leverages future weapons designs**
- **Produces data used as inputs to training simulators**

It saves lives!

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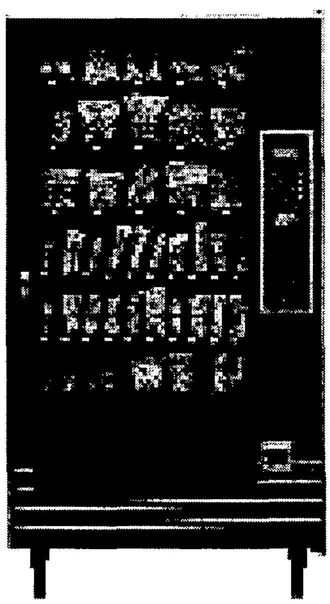
Change

Change is inevitable,
except from a vending machine.



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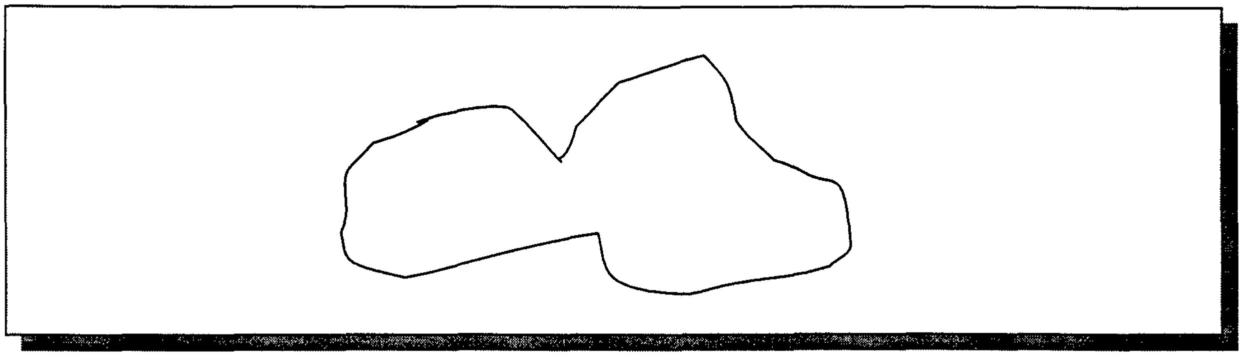

THINK
ASYMMETRICALLY

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OUTLOOK

A PERSONAL VIEW

"PEACE IS THE TIME
BETWEEN CONFLICT
WHEN NATIONS TAKE
TIME TO RELOAD"

OVERVIEW OF STRUCTURAL DAMAGE TOLERANCE HISTORY AND TRENDS

Robert G. Eastin
FAA NRS
Fracture Mechanics/
Metallurgy

FAA97003
10/9/97

INTRODUCTION

The following presentation briefly overviews the history of airframe damage tolerance and reflects on some perceived trends in this area. It is based on this National Resource Specialists perspective and should not be interpreted as official FAA position or policy.

The National Resource Specialist program was established in 1979 and was implemented to attract and maintain a group of technical experts in various core disciplines whose technical expertise could be drawn on, as required, by the FAA, other U.S. Government Agencies, foreign civil aviation authorities and the aviation industry. Nineteen (19) technical disciplines have been identified which includes Fracture Mechanics. Other structures related disciplines are Flight Loads/Aeroelasticity, Nondestructive Evaluation, Metallurgy, Advanced Composites, and Crash Dynamics. You are encouraged to take advantage if this resource.

ALOHA 737 - APRIL 1988

FAA97003
10/9/97

ALOHA 737 - APRIL 1988

A discussion on airframe damage tolerance would not be complete without some mention of the Aloha 737 incident. This always stimulates thinking on the many different aspects of damage tolerance. The damage seen here was precipitated by the existence of relatively small multisite cracks at fastener holes in a fuselage longitudinal splice. The structure was intolerant to this damage and a large portion of the fuselage above the floor was lost during flight. Fortunately, the remaining structure had enough inherent tolerance to this large damage for the aircraft to land, although one life was lost. This incident, combined with increasing concern with respect to the potential impact of undetected multisite fatigue damage, was the catalyst for the aging aircraft initiatives which were launched shortly afterwards.

PRE 1974 DESIGN PHILOSOPHIES

- ADEQUATE STATIC STRENGTH PROVIDED BY DESIGNING <u>UNDAMAGED</u> STRUCTURE TO WITHSTAND SPECIFIED CONDITIONS, FACTORED BY 1.5, WITHOUT FAILURE
- ADEQUATE SERVICE LIFE INSURED BY SAFE-LIFE DESIGN
- MULTIPLE LOAD PATH DESIGN EMPLOYED TO ENHANCE SAFETY, AS A STANDARD PRACTICE, AND/OR AS A CERTIFICATION ALTERNATIVE TO SAFE-LIFE - (THIS PHILOSOPHY WAS TYPICALLY APPLIED BY EVALUATING STRENGTH CAPABILITY WITH A SINGLE LOAD PATH OMITTED WITHOUT CONSIDERING DAMAGE IN THE SURROUNDING STRUCTURE)

PRE 1974 DESIGN PHILOSOPHIES

Prior to 1974 there were three primary design philosophies used for aircraft. First, basic static strength was insured by designing well (or undamaged) structure to be able to withstand, without catastrophic failure, specified design (i.e. limit) conditions factored up by 1.5. This practice had been successfully used for many years to preclude single loading event failures within the operating design envelope. Concerns over premature loss of structural integrity due to fatigue were the motivation for use of the safe-life philosophy wherein the structure was designed to be free from detectable cracks for a certain period of time (i.e. design life goal). Application of this approach required testing for periods significantly in excess of the design life goal. The third philosophy involved the use of multiple load paths and was standard practice by many companies to provide extra forgiveness in the presence of unplanned damage. The multiple load path or "fail-safe" approach was also an option, provided in the original version of FAR 25.571, to certification as safe-life. In practice this approach involved assessing load carrying capability with a single element omitted without considering coexisitng damage in the adjacent structure.

RELEVANT SERVICE EXPERIENCE

(THRU 1977)

- SIGNIFICANT/CATASTROPHIC FATIGUE CRACKING, ON AIRCRAFT DESIGNED AND TESTED USING SAFE-LIFE APPROACH, DUE TO LESS THAN PLANNED FOR INITIAL MANUFACTURING QUALITY
  - KC-135, F-5, F-111, ,C-133
- LOSS OF AIRCRAFT DUE TO FAILURE OF "FAIL-SAFE" MUTIPLE LOAD PATH STRUCTURE AS A RESULT OF UNDETECTED MULTI-SITE CRACKING
  - HAWKER SIDDLEY 748 (ARGENTINA, 1976)
  - B707 (ZAMBIA, 1977)
- SAFE RETURN OF AIRCRAFT, WHICH HAD SUFFERED SIGNIFICANT AMOUNTS OF DAMAGE, BECAUSE OF INHERENT DAMAGE TOLERANCE
  - TOUGH MATERIALS (E.G. 2024-T3)
  - BUILT-UP, CONVENTIONALLY FASTENED ASSEMBLIES

FAA97003
10/9/97

RELEVANT SERVICE EXPERIENCE

Service experience demonstrated the strengths and weaknesses of the design philosophies which had been used to address loss of structural integrity due to damage (e.g. fatigue cracking). Incidents of fleet wide cracking and catastrophic loss of aircraft experienced by the Air Force was painful evidence that the safe-life philosophy by itself was inadequate. The failure to address less than planned for initial manufacturing quality was at the root cause. Confidence in the multiple load path or "fail-safe" approach was also shaken when aircraft were lost due to the unexpected catastrophic failure of "fail-safe" structure. Undetected cracking resulting from lack of inspections consistent with structural damage tolerance characteristics was the root cause. On the positive side were a significant number of incidents where aircraft safely landed after having experienced major inflight damage (e.g. fuselage damage due to propeller loss). This success can be attributed to the inherent damage tolerance of the materials used and the multiple load path design which was employed.

LESSONS LEARNED

- FAILURE TO DESIGN AND/OR ESTABLISH INSPECTION PLANS BASED ON THE ASSUMPTION THAT UNPLANNED STRUCTURAL DAMAGE WILL OCCUR CAN LEAD TO UNSAFE CONDITIONS
- "FAIL-SAFE" DESIGN WITHOUT CORRESPONDING DIRECTED INSPECTIONS, AT APPROPRIATE INTERVALS, IS NOT TRULY FAIL-SAFE
- FATIGUE CRACKING AT MORE THAN ONE LOCATION SHOULD BE ADDRESSED, ESPECIALLY AS THE AIRFRAME AGES
- MULTIPLE LOAD PATH STRUCTURE CAN PROVIDE A LEVEL OF INHERENT DAMAGE TOLERANCE SUCH THAT AN UNPLANNED IN-SERVICE MISHAP IS SURVIVABLE

LESSONS LEARNED

Service experience indicated that unplanned for damage (e.g. material defects, poor initial manufacturing quality, etc.) will occur and unless actions are taken to compensate for it safety m^y deteriorate to unacceptable levels. It also indicated that so called "fail-safe" design may result in a false sense of security and cannot, by itself, result in an adequate level of safety. Experience shows us that this is especially true as the aircraft ages and the probabilty of cracking at more than one location increases. Experience has also illustrated the virtues of multiple load path structure and its forgiveness with respect to unplanned for large scale damage.

FORMAL DAMAGE TOLERANCE REQUIREMENTS

- USAF MIL-A-83444, "AIRPLANE DAMAGE TOLERANCE REQUIREMENTS", ISSUED IN JULY 1974
  - APPLICABLE TO THE DESIGN OF ALL USAF AIRCRAFT
  - REQUIRES ASSUMPTION OF A ROGUE FLAW IN THE MOST CRITICAL AREAS OF ALL SAFETY OF FLIGHT STRUCTURE
  - REQUIRES RESIDUAL STRENGTH TO BE MAINTAINED TO MINIMUM LEVELS FOR MINIMUM TIME PERIODS DEPENDING ON DESIGN CONCEPT AND INSPECTABILITY
- FAA AMENDMENT 45 TO FEDERAL AVIATION REGULATIONS (FAR) PART 25 ISSUED DECEMBER 1978
  - APPLICABLE TO COMMERCIAL TRANSPORT AIRCRAFT
  - DAMAGE TOLERANCE EVALUATION REQUIRED
  - MINIMUM RESIDUAL STRENGTH LEVELS SET
  - REQUIRES ESTABLISHMENT OF INSPECTION PLAN CONSISTENT WITH DAMAGE TOLERANCE CHARACTERISTICS OF STRUCTURE

FAA97003
10/9/97

FORMAL DAMAGE TOLERANCE REQUIREMENTS

Formal damage tolerance requirements were adopted for the design of new aircraft in response to lessons learned. The Air Force issued MIL-A-83444 in July of 1974. This was intended for application to the design of all new USAF aircraft. It recognized the potential impact of less than planned for initial quality and required the assumption of a rogue flaw. It also linked inservice inspection requirements to the damage tolerance characteristics of the design by specifying minimum residual strength levels tied to inspection types and intervals. The FAA issued amendment 45 to Part 25 in December 1978. This was applicable to the certification of all new large commercial transport aircraft and mandated that a damage tolerance evaluation be performed. It requires minimum levels of residual strength to be maintained by establishing inspection plans consistent with the damage tolerance characteristics of the structure.

CURRENT TRENDS

- INCREASING RECOGNITION OF THE IMPORTANCE OF ACCOUNTING FOR UNPLANNED DAMAGE

- INCREASING COLLABORATION BETWEEN DOD, FAA, NASA, INDUSTRY, ACADEMIA, ETC. WITH RESPECT TO ENHANCING DAMAGE TOLERANCE OF NEW AND EXISITING AEROSPACE SYSTEMS

- MORE WIDE SPREAD ADOPTION OF DAMAGE TOLERANCE REQUIREMENTS FOR NEW DESIGNS
  - ROTATING ENGINE COMPONENTS ?
  - ROTORCRAFT?
  - SMALL AIRCRAFT?

CURRENT TRENDS

The role of damage tolerance in the design of new structure and management of existing systems is in a state of flux. An increasing recognition of the importance of planning for the unplanned is drawing more and more attention to its value in maintaining and enhancing safety. Because of this we are seeing a new era of cooperation and collaboration between designers, operators, maintainers, regulators and researchers. It is believed that we will also see adoption of damage tolerance philosophies for other than military aircraft and large commercial transports. This may include rotating engine components, rotorcraft, and small aircraft.

CURRENT TRENDS (cont'd)

- USE OF DAMAGE TOLERANCE EVALUATION RESULTS USING WORST CASE MANUFACTURING DEFECT SIZES TO SET THRESHOLD POINT FOR INSPECTIONS?
- INCREASING ECONOMIC PRESSURES WORKING AGAINST ENHANCED DAMAGE TOLERANCE
  - PREMATURE USE OF NEW MATERIALS
  - PREMATURE IMPLEMENTION OF NEW MANUFACTURING PROCESSES
  - DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA) INITIATIVES RESULTING IN LARGE INTEGRAL COMPONENTS
  - COSTS ASSOCIATED WITH FULL SCALE FATIGUE AND DAMAGE TOLERANCE TESTING

CURRENT TRENDS (cont'd)

There is a strong case to be made for setting initial inspection points for principle structural elements based on rogue flaw assumptions. This notion is not universally embraced. However, given enough time and some more adverse service experience, it may be.

Even with the increased sensitivity to the importance and value of the damage tolerance approach and trends towards expanding its application and use, there still are some factors that will challenge us in maintaining and enhancing damage tolerance in new systems. New untried and unproved materials will be proposed for cost and/or weight savings. New manufacturing processes intended to save cost will be proposed. Care must be taken to adequately understand their impact on damage tolerance so informed decisions can be made with respect to implementation. Designing for manufacture and assembly efficiency will result in large integral components which have less inherent damage tolerance. Finally, the costs associated with testing will work against having the comprehensive development and qualification basis needed to move forward confidently with new materials, manufacturing processes and design concepts.

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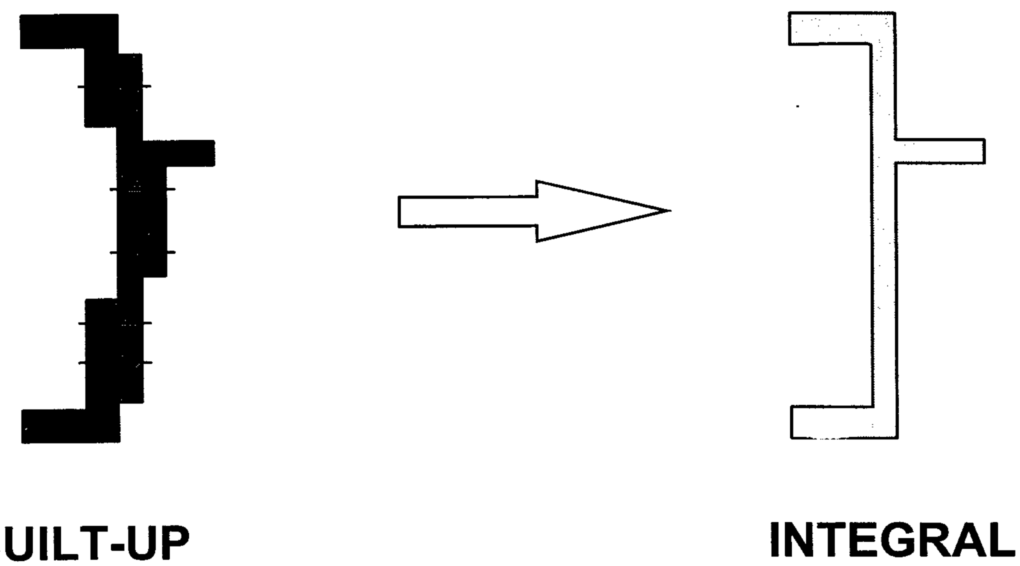
INTEGRAL STRUCTURE

- INTEGRATING PARTS CAN SIGNIFICANTLY REDUCE ASSEMBLY COSTS



- CRACK CONTAINMENT BY ARRESTMENT AND/OR CRACK TURNING IS DIFFICULT TO INSURE/VALIDATE
- PAST EXPERIENCE SHOWS THAT BUILT-UP STRUCTURE IS INHERENTLY MORE DAMAGE TOLERANT THAN ITS INTEGRAL COUNTERPART

INTEGRAL STRUCTURE

Integrating structure can be a very efficient way to reduce system cost. Reduced part count and elimination of assembly steps can offer atractive savings. When this is done it must be recognized that extra care and effort must be given to understanding damage tolerance characteristics. Although crack containment and even arrest is possible to attain in integral strucutre it is difficult to insure and demonstrate with high confidence. The much greater inherent damage tolerance of built-up structure has proved its value in the past and shouldn't be overlooked when weighing recurring system costs against development costs and inherent system survivability. This is especially the case for structure which will be exposed to a known threat (e.g. burst engine disk, battle damage, etc.).

SUMMARY

- IN-SERVICE EXPERIENCE HAS DEMONSTRATED THE SHORT COMINGS OF THE SAFE-LIFE AND “OLD” FAIL-SAFE APPROACHES
- DAMAGE TOLERANCE REQUIREMENTS, ADOPTED FOR MILITARY AIRCRAFT DESIGN AND COMMERCIAL TRANSPORT AIRCRAFT CERTIFICATION, LINK DAMAGE TOLERANCE CHARACTERISTICS AND IN-SERVICE INSPECTION REQUIREMENTS
- INCREASED SENSITIVITY TO THE POTENTIAL IMPACT OF UNPLANNED DAMAGE SHOULD RESULT IN SAFER AEROSPACE SYSTEMS
- ECONOMIC PRESSURES WILL PRESENT SIGNIFICANT CHALLENGES WITH RESPECT TO IMPLEMENTION OF NEW DAMAGE TOLERANT DESIGNS

SUMMARY

Inservice experience has taught us the shortcomings of the safe-life and fail-safe design philosophies as applied in the past. This set the stage for adoption of damage tolerance based requirements for the design of USAF aircraft and later for the certification of large civil transport aircraft. This plus an ever increasing sensitivity to the potential impact of unplanned damage should result in wider application of damage tolerance principles and thus safer aerospace systems. However, care must be taken since economic pressures will continue to challenge us with respect to implementing new damage tolerant designs.

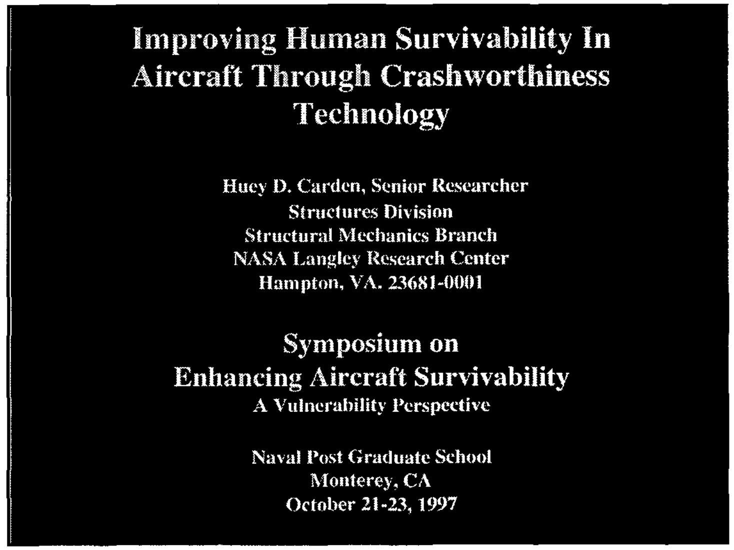
Improving Human Survivability In Aircraft Through Crashworthiness Technology

Huey D. Carden, Senior Researcher
Structures Division
Structural Mechanics Branch
NASA Langley Research Center
Hampton, VA. 23681-0001

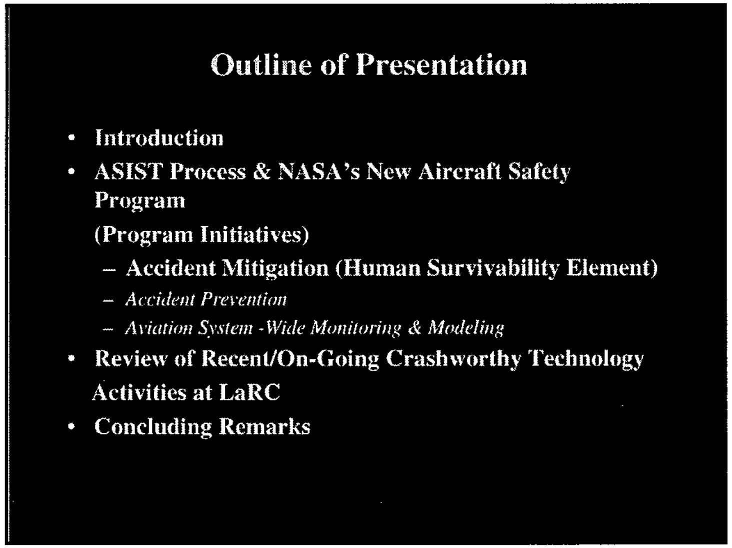
Symposium on Enhancing Aircraft Survivability

A Vulnerability Perspective

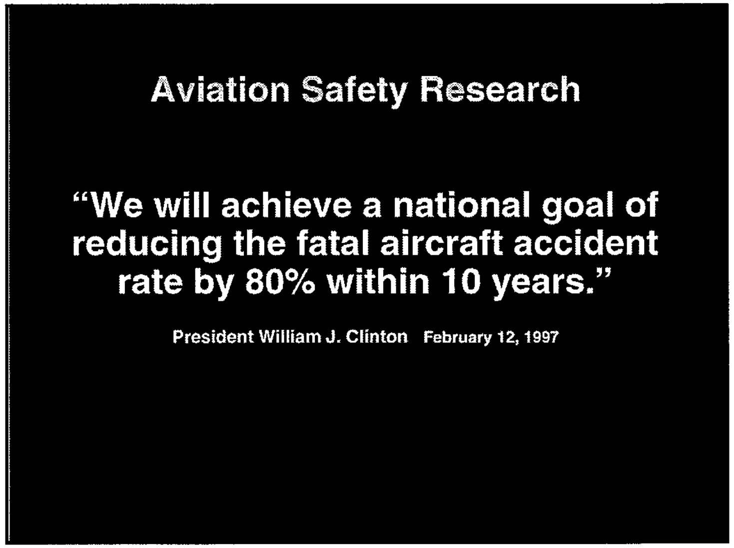
Naval Post Graduate School
Monterey, CA
October 21-23, 1997



- **My name is Huey Carden. I'm from NASA's Langley Research Center in Hampton, VA.**
- **I'd like to talk a few minutes this morning about Improving Human Survivability in Aircraft Through Crashworthiness Technology.**
- **I believe that Human Survivability is the ultimate goal of Enhancing Aircraft Survivability which is the subject of this Symposium.**



- **I'll try to follow this outline and discuss briefly the ASIST Process (I'll explain this shortly) and the NASA Aircraft Safety Program which has Initiatives Including:**
    - **Accident Mitigation (Human Survivability) which I'll cover, and**
    - **Accident Prevention and System-Wide Monitoring and Modeling which I'll not discuss.**
- **I'll review some recent/ongoing crashworthy technology activities at LaRC that directly support Human Survivability, and**
- **Make a few Concluding Remarks.**

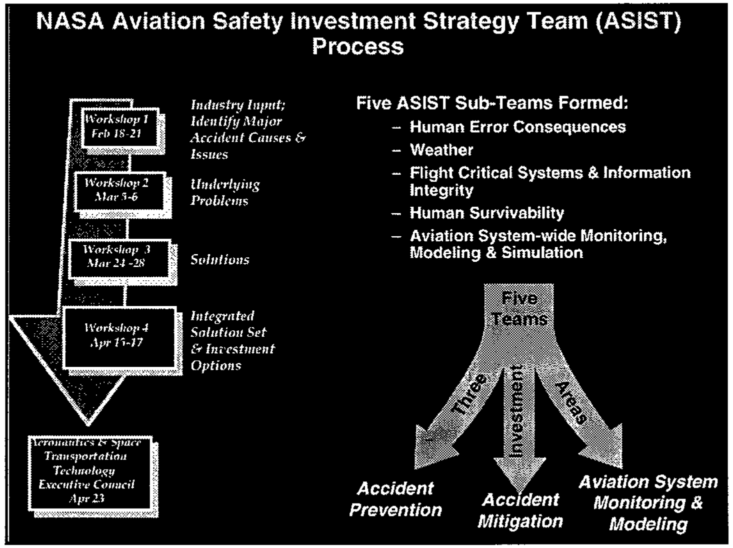


- **As many or all of you may know, the President announced in early Februrary the national goal of reducing the fatal aircraft accident rate by 80% in 10 years.**

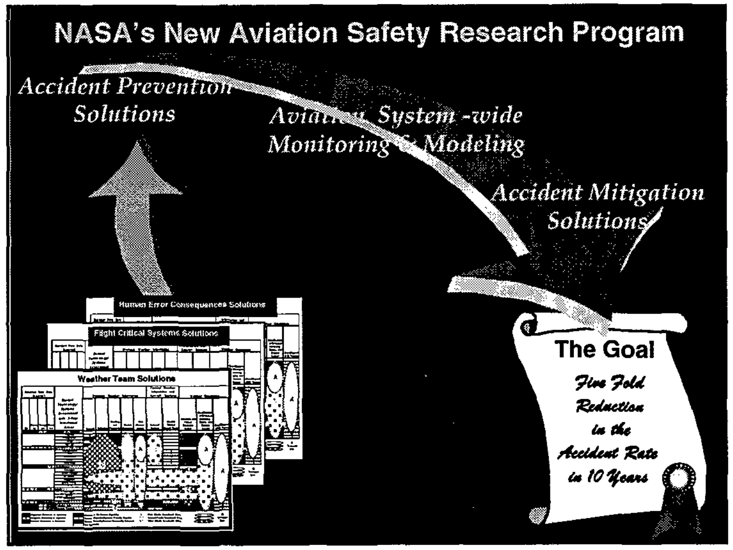
ASIST Process and Planning for NASA's New Aircraft Safety Program (ASP)

- **As a result of that announcement, NASA committed to supporting that goal and initiated the ASIST process that was the precusor to the formulation of the NASA Aircraft Safety Program (ASP)**

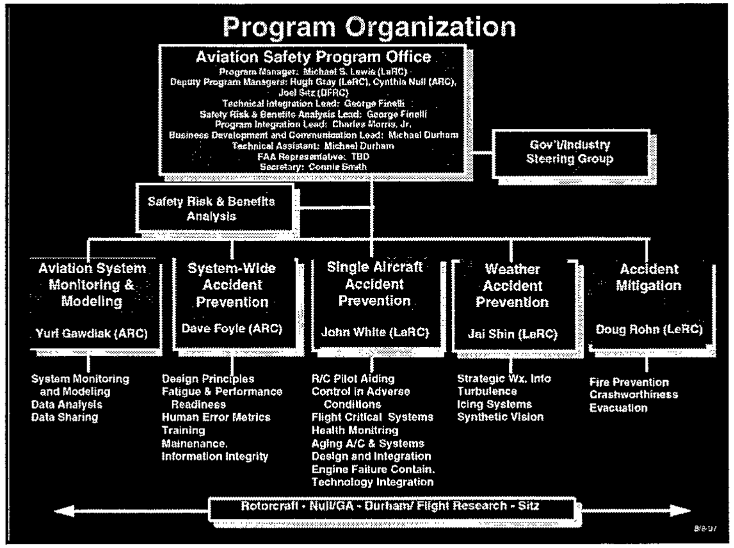
- **ASIST stands for Aviation Safety Investment Strategy Team.**
- **The core group was from NASA, FAA, and DoD.**
- **Chaired by Charlie Huettner of NASA headquarters, Code R FAA, DoD Weather, and Industry reperesenatives as listed completed the core group.**
- **Five focus areas (See List) were to be covered in the ASIST process.**



- The process involved the formation of 5 sub-teams to focus on the areas : (See List on Right).
- I co-chaired the Human Survivability with Gary Frings of the FAA Tech Center.
- A series of Workshops were held, the 1st being just 6 days after the President's announcement, followed by three others, culminating in a combined presentation from all five sub-teams to NASA's Aeronautics and Space Transportation Technology Executive Council on April 23rd.
- From the 5 areas, 3 investmnent areas were identified : Accident Prevention, Accident Mitigation (Human Survivability), & System-Wide Monitoring).

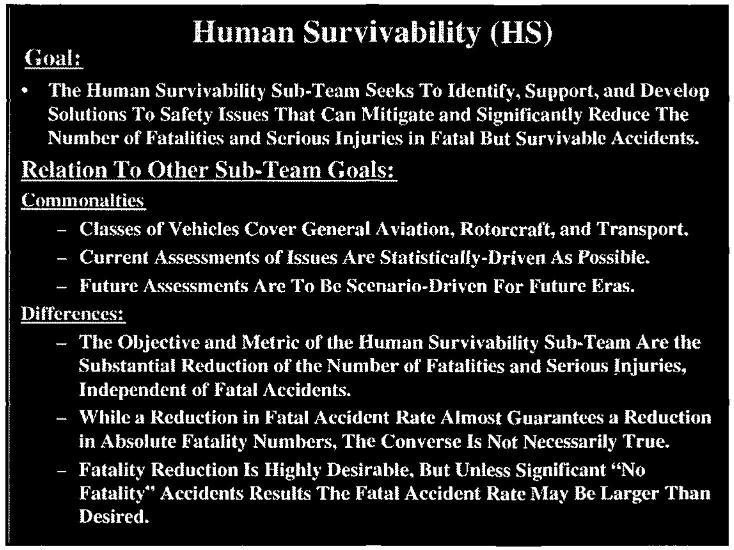


- The process used by all the sub-teams was :
    - From statistics (as possible) identify the major (fire, impact, weather, etc) causes of fatalities and serious injuries in accidents,
    - Look for underlying contributors to the major causes, identify potential solutions, assess the current research activities relative to those areas, identify gaps and propose research investments to provide soultions/ improvements in those areas.
- This process led to the 3 potential investment areas addressing safety issues which can help to realize the national goal.
- NASA alone or any other organization alone can not achieve the goal. It will take the combined efforts of many organizations.



- Following the ASIST Process, an RFP was issued to the various NASA Centers to compete which Center would be lead for the new Aircraft Safety Program.
- Langley was selected.
- The Program Organization is shown here with many of the positions filled.
- The 3 Major Investment areas are shown with Prevention (the largest) being composed of the three areas shown, along with the System Monitering and the Accident Mitigation (Human Survivability).
- Cross-cutting representation of Rotorcraft/GA and Flight Testing are included across all investment areas.

- With respect to the Human Survivability Team, this slide shows the participants with time.
- The numbers grew over the course of the four workshops.



- **The goal of the Human Survivability Team is stated above.**
- **The commonalties in relation to the other sub-teams is also given, however,**
- **A major differences, stressed from the outset, is indicated.**
    - **Human Survivability must focus on reducing the fatalies and serious injuries independent of fatal accidents.**
- **Without 100% success of Human Survivability Technology in reducing the <u>number of fatal accidents</u> (with survivors) to <u>no fatalities status</u>, the fatal aircraft <u>accident rate</u> will not necessarily be reduced as desired.**

Human Survivability

Accident Statistics And Expert Advice Were Used To Guide Planning Efforts And Priority In Human Survivability

Aircraft Category →	Transport World Wide 82-94(14 yr)	Transport World Wide 82-94 (14 yr)
Fatal Accident Area	Number of Accidents	OnBoard Fatalities
Landing	173	290
On-Ground Fire	93	1082
ATC Com.	61	2111
Maint. & Insp.	58	1560
CFIT	49	2890
Loss of Control	45	2632
Ground Ops	33	162
Engine/Crew	21	346
Approach	20	1257
TakeOff Conf.	13	243
Inflight Fire	12	673
Uncontained Engine	13	199

+ Additional Data Mining
+ Expert(s) Advice

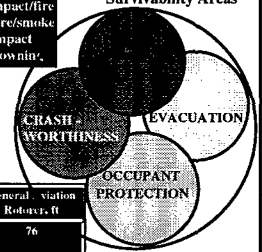
1959-90
Accident Data Show:

52% Nonsurvivable — 50% Impact/fire
3% 1-3 survivors — 27% Fire/smoke
45% survivable — 18% Impact
5% Drowning

1985-1995

Aircraft Category ►	General Aviation-All	General Aviation Rotorcraft
Fatal with at least one survivor	701	76
Accidents with fire	2624	194
Fatal Accidents with fire	1588	101
Total Fatal Accidents	4979	359

Interrelated Human Survivability Areas



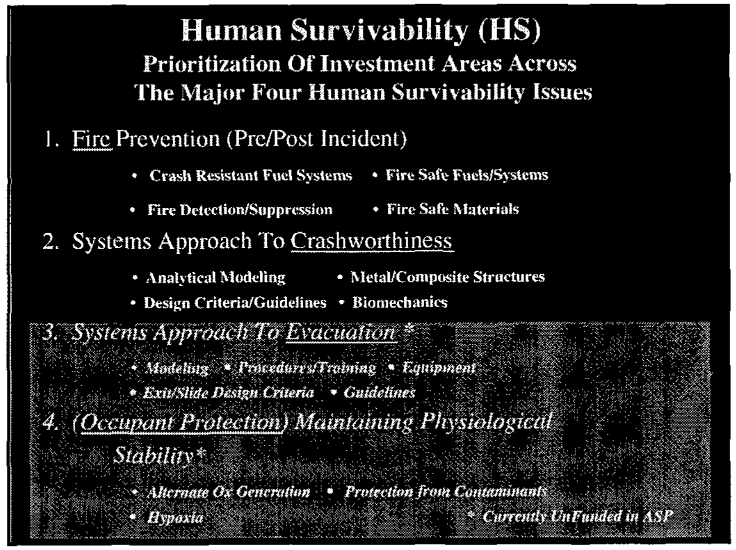
Human Survivability (HS)

Challenges/Objective of HS Investments

- Challenges/Objective of Fire Investment :
  To Identify, Support, and Develop Fire Prevention, Detection, and Suppression Concepts That Can Minimize Fire Hazards in Crashes and In-Flight Incidents.
- Challenges/Objective of Crashworthiness Investment:
  To Develop A Systems Approach To Crashworthiness Design That Includes Validated Analysis Methodology, New Structural Concepts And Materials, Safer Cabin Interiors Design, Advanced Restraint Equipment, Design And Injury Criteria To Enhance Crash Safety.
- Challenges/Objective of Evacuation Investment :
  To Develop A Systems Approach For Evacuation That Includes Analysis/ Simulation Methodology, New Procedures ,Training, Equipment, And Design Criteria Which Can Enhance And Provide Means For More Timely Evacuation During Fire In Aircraft Accidents.
- Challenges/Objective of Occupant Protection Investment:
  To Develop Detection/Warning Means, New Procedures ,Training, And Equipment Which Can Provide Occupant Protection From Fire Related Hazards And Thus Provide Additional Evacuation Time.

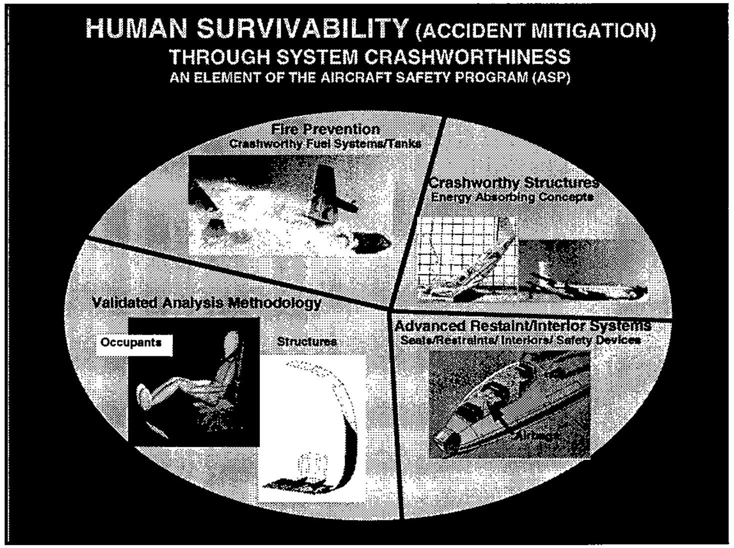
All the Challenges/Objectives Are Aimed At Mitigation/Reduction of Fatalities and Serious Injuries In Current As Well As New Aircraft Configurations.

- **The challenges and objectives of the four major potential investment areas are stated above.**

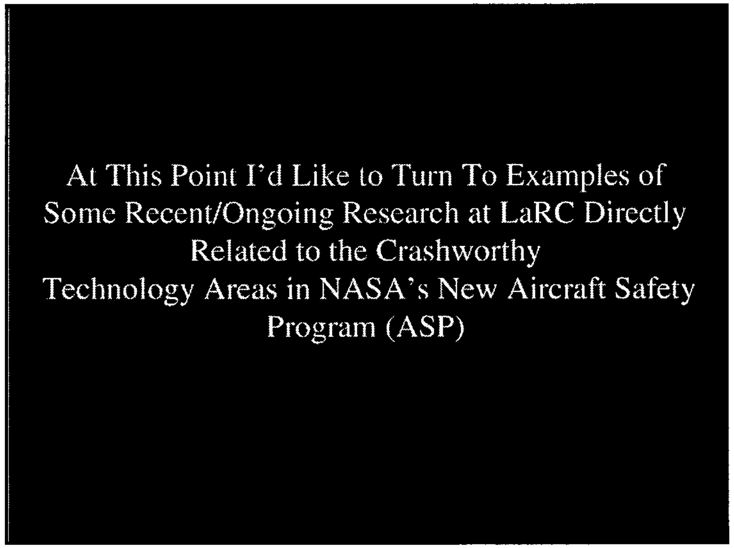


- **The Prioritized Investment Areas are shown here with Fire Prevention and Systems Approach to Crashworthiness being the number 1 and 2 priority areas.**
- **3rd priority is Systems Approach to Evacuation -- on the "bubble" for potential funding, and**
- **Occupant Protection is the 4th priority area.**
- **These Investment areas were included in the sum total of the other sub-team findings and recommendations, all of which were also prioritized by the entire ASIST team.**
- **Evacuation and Occupant Protection are not currently included in the program due to funding limitations and priority.**

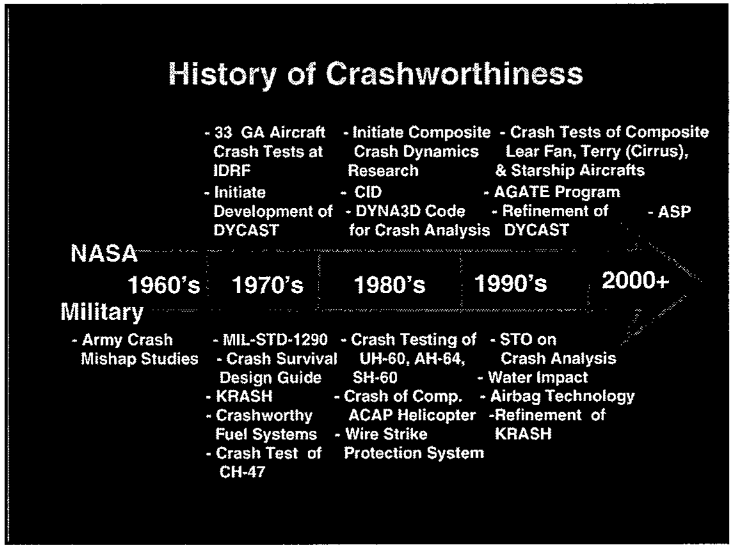
- **Planning workshops on the various subjects listed above have been and are on-going to plan program activities in the investment areas across the entire ASIST spectrum.**
- **Fire and Crashworthiness activities began in July and will continue through December for laying out the efforts in 98 and beyond.**
- **The next Crashworthiness workshop is planned for December 8 - 9, 1997 at Langley Research Center.**



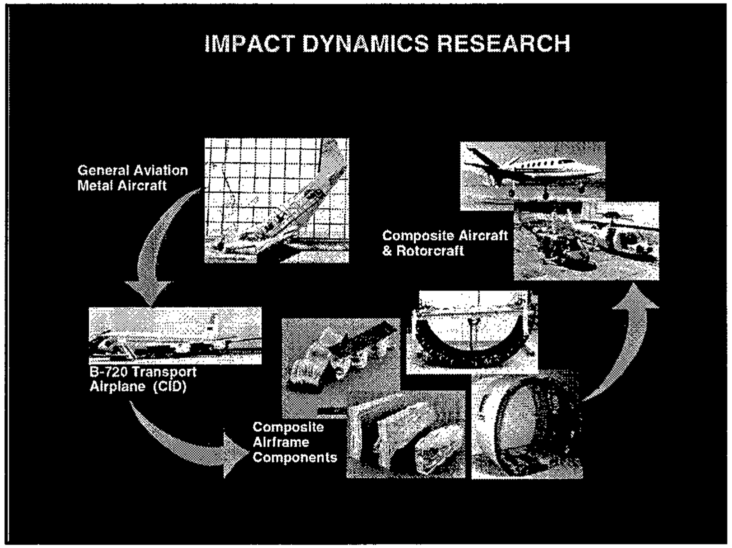
- Thus, in summary, Human Survivability (Accident Mitigation) through Systems Approach to Crashworthiness is an element of the New NASA Aircraft Safety Program.
- Areas of the Crashworthiness Focus Include a Fire Prevention Element, Energy Absorbing Crashworthy Structures, Interiors and Safety Restraint Systems, and Validated Structural and Occupant Analysis & Modeling
- All these activities are aimed at enhancing Human Survivability through Crashworthiness Technology.



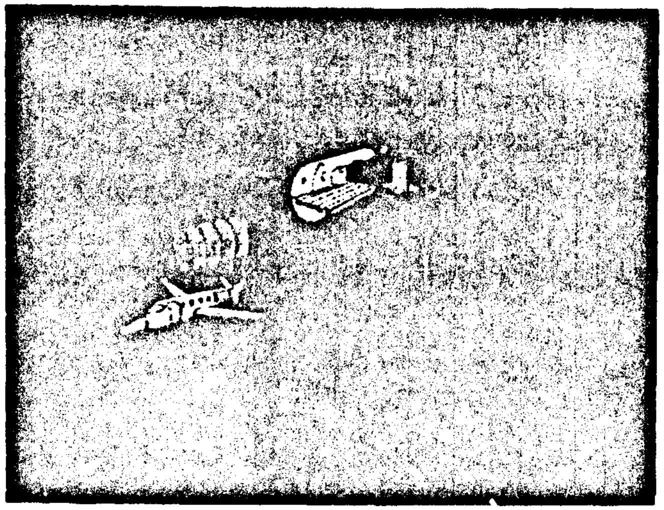
- **At This Point I'd Like to Turn To Examples of Some Recent/Ongoing Research at LaRC Directly Related to the Crashworthy Technology Areas in NASA's New Aircraft Safety Program (ASP)**



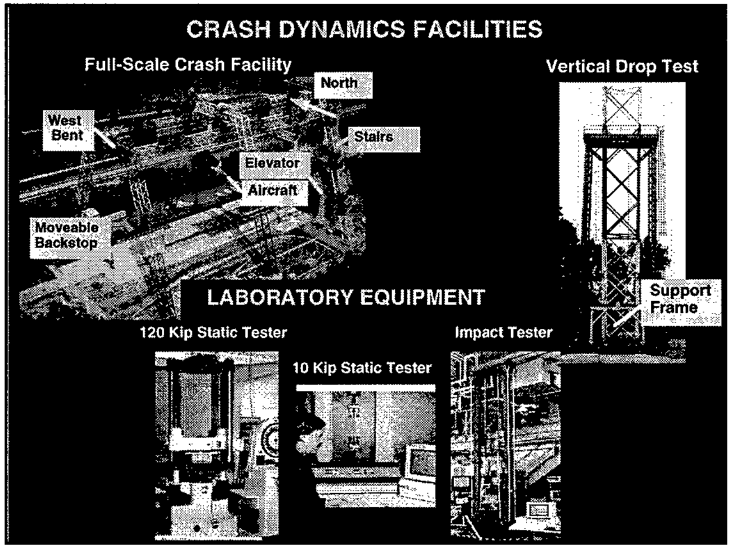
- Some of the major activities in crashworthiness research by NASA LaRC is illustrated along with Army focuses which has involved our support with full-scale tests of helicopter safety systems such as wire strike systems, airbags, fuel cells, etc.
- Our involvement goes back to the late 60's with the start of the GA metal aircraft crash test program and analytical development of computer tool.
- Shift to transport emphasis occurred with CID in mid 80's.
- Parallel to CID was beginning of focus on composite structures for aircraft.
- In the 90's we have tested composite aircraft under crash loads to build database and now the 00's hold the new Aircraft Safety Program efforts.



- This is a pictorial representation of the data on the previous slide showing the progression of LaRC efforts in Crashworthiness for enhancing human survivability.
- It shows the GA metal aircraft work, the shift to transport emphasis with CID, and paralleling that the movie into composite structures and full-scale composite aircraft efforts.



- The elements of the Composite Impact Dynamics efforts are shown above.
- The elements include database and innovative concepts, companion analysis, scaling studies for potential relief from full-scale structural requirements, and the full-scale testing where possible.
- All the efforts are aimed at developing a fundamental understanding of composite structures behavior under crash loads and the development of improved design to enhance human survivability through crashworthiness technology.

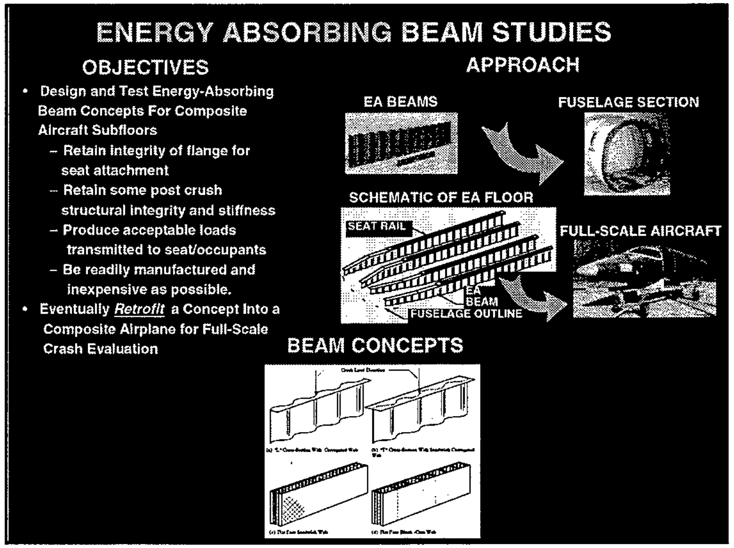


- Facilities at LaRC for use in Crashworthiness Technology efforts are shown.
- We have a full-scale crash facility (Former Lunar Landing Facility for training astronauts for moon landing) converted in late 60's to do full-scale aircraft crash tests.
- Facility is a 240' high, 400' long gantry under which we suspend fully instrumented test articles (up to 40,000 lbm) for crash testing under controlled conditions.
- We also have a vertical drop facility under one leg of the gantry for vertical tests up to 707 cross-section size.
- Various static test equipment is use in the lab for components testing, and an Impact Tower is available for dynamics component tests.
- Data acquisition and analysis is done on a computer based system.

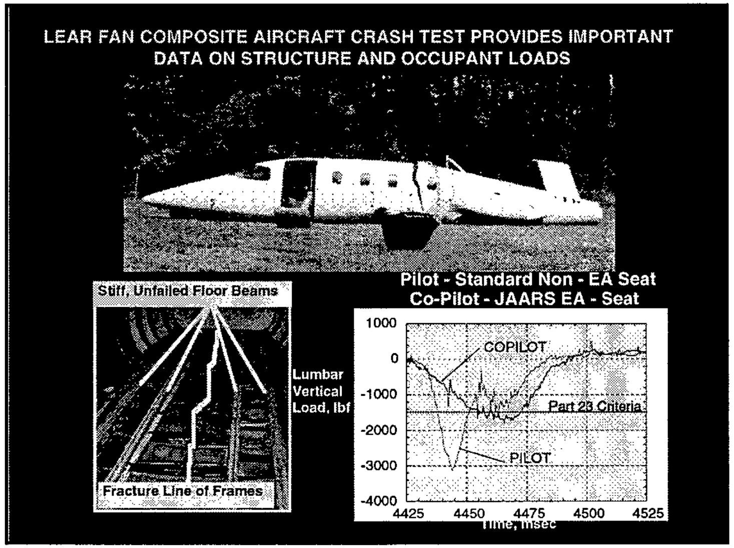
HUMAN SURVIVABILITY REQUIREMENTS

- MAINTAIN SURVIVABLE VOLUME
  - FUSELAGE CAGE
- RESTRAIN OCCUPANT WITHIN SURVIVABLE VOLUME
  - STANDARD RESTRAINTS
  - INFLATABLE RESTRAINTS
  - PRETENSIONERS
- LIMIT OCCUPANT LOADS
  - ENERGY ABSORBING SEATS
  - ENERGY ABSORBING SUBFLOORS
  - ANTI-PLOWING FUSELAGE STRUCTURES
  - LOAD LIMITERS & PRETENSIONERS
- MITIGATE POST-CRASH HAZARDS
  - Evacuation
  - Fire
  - Water

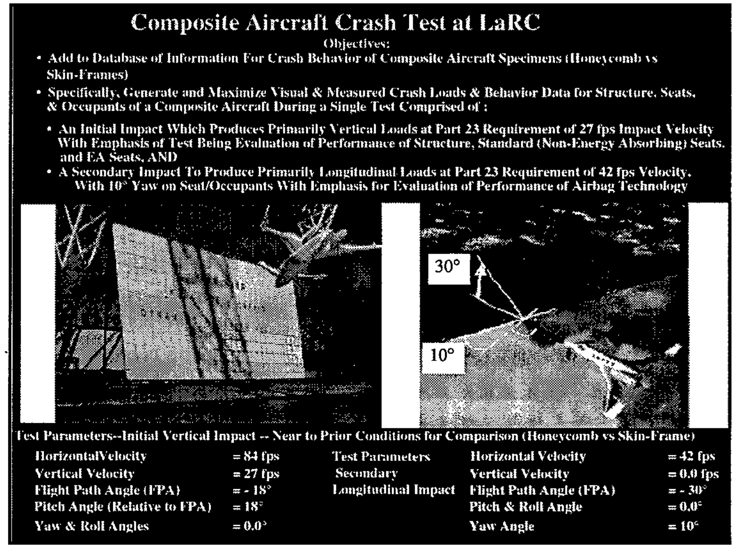
- **Whenever an effort is undertaken in crashworthiness it should address some aspect of the requirements for Human Survivablity.**
- **Those requriements are:**
  - **Maintain livable volume**
  - **Restraint the occupant within the volume**
  - **Limit the loads to the occupant**
  - **Minimize the post crash hazards**
- **The next few slides illustrate some of our efforts.**



- A particular effort which involves the element level, the component level and the full-scale level is an Energy Absorbing Beam Study.
- Objectives of the study are listed above left. Approach is illustrated at the right.
- Various composite beam concepts (bottom center) are being designed, fabricated, and tested, both statically and dynamically.
- Aircarft sections (component level) when possible are modified for evaluation with EA beam concepts.
- A down-select will be made for incorporation into a full-scale aircraft for evaluation of crash performance.

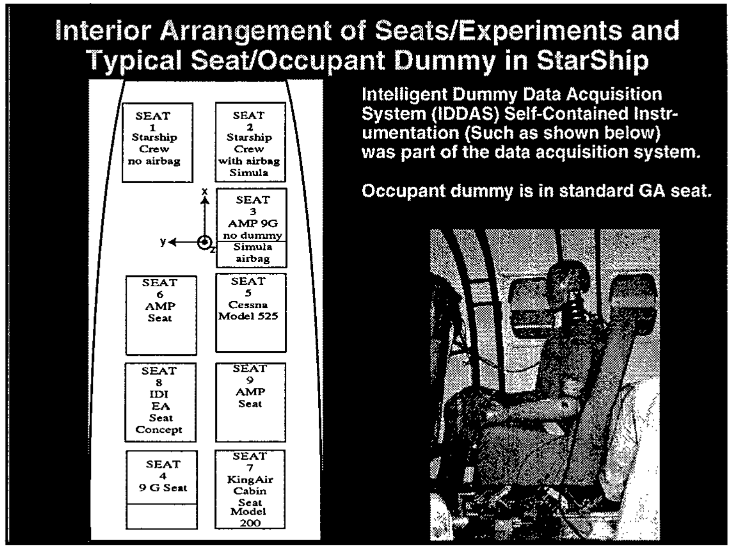


- Part of the impetus for the EA beam work of the previous slide is shown here.
- A full-scale LearFan composite skin-frame construction aircraft was crash tested for database information and crash evaluation.
- The test was a flat impact at 31 fps vertical, 84 fps longitudinally.
- High g loads (250 g's, 7-8 msec) at the floor/seat attachments lead to excessive occupant loads.
- Failure was fracturing of all the composite frames along the bottom of the aircraft floor region. No failure occurred in the metal floor beams beneath the seat rails.
- Pilot spinal load in non-EA seat was over 3000 lbf while the co-pilot in a JAARS EA concept was slightly over the Part 23 requirement of 1500 lbf.

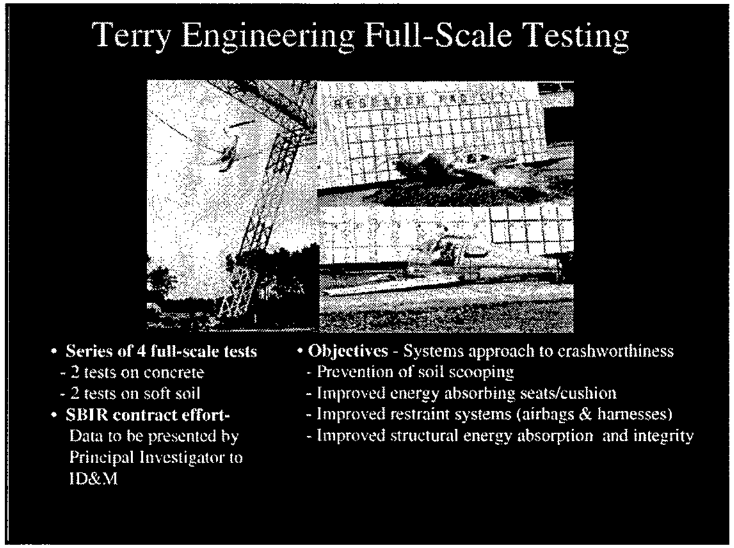


- **Additional crash testing of a honeycomb construction for comparison to the skin-frame of the Lear has been conducted.**
- **Test was designed to give:**
    - **Initial flat impact 27 fps vertical 84 fps longitudinal (close to previous Lear parameters) for primary vertical loads to evaluate structure, seats and restraints performance,**

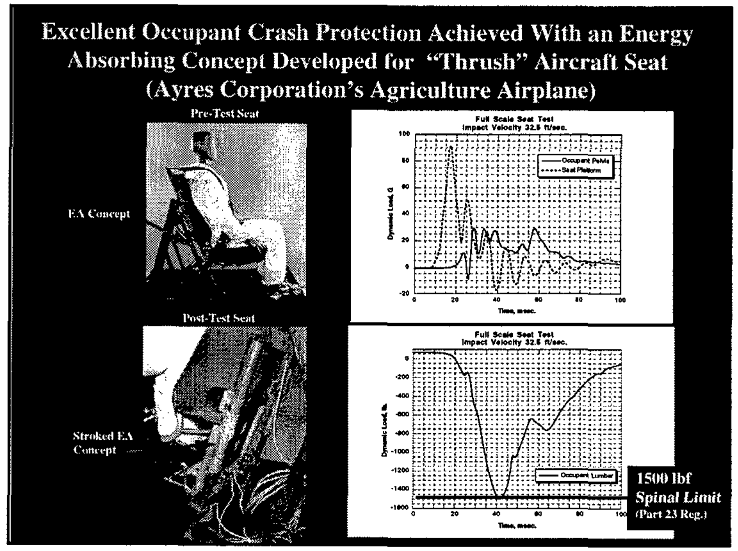
      and
    - **A secondary test with longitudinal inputs at 42 fps, 10 degree yaw into an dirt embankment for airbag technology assessment.**



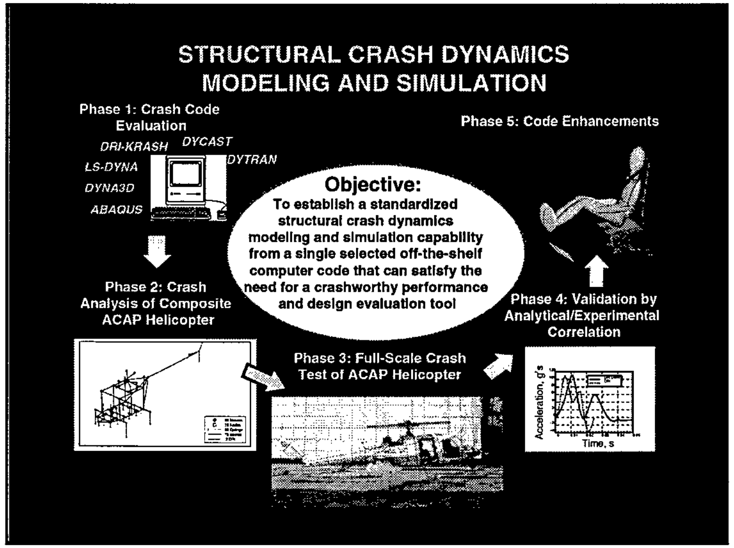
- **Interior seating arrangement (EA and standard), and airbag set-up are shown above.**
- **Right figure shows one of the self-contained instrumented dummy occupants used along with our own instrumented occupant dummies.**
- **Cockpit airbag was in co-pilot position beside pilot without airbag.**
- **A standard 9 g seat with airbag on back was in front of occupied position for testing empty seat situation.**
- **Other standard seats from a manufacturer a second EA seat concept were on-board.**



- We have also conducted 4 other composite aircraft crash tests supporting a SBIR effort by Terry Engineering and Cirrus Design.
- Two tests were onto concrete and two were into soft soil.
- Objectives are listed above.
- Data are being shared with the AGATE Integrated Design and Manufacturing Work Package members.
- AGATE's ID&M has a major crashworthiness element in that program.



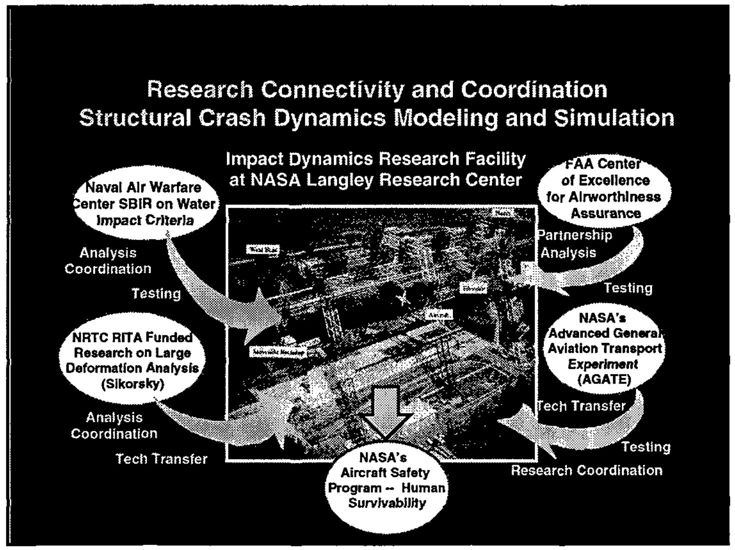
- An activity with EA seat application for enhancing human survivablity is shown here.
- Existing aircraft seat for an agriculture aircraft was modified to include EA concept that if it failed to operate was no worse than the original seat performance.
- Minimial weight added (weight was not a critical factor).
- Tested at 32.5 fps vertical impact velocity, with resulting peak of 90 g's approximately 20 msec duration applied to seat attachment points.
- G's on occupant were about 15 g's, but more importantly the compressive spinal load at 32. 5 fps did not exceed 1500 lbf Part 23 requirement at a lower impact velocity !
- Technology information has been transfered to Ayres Corporation for whatever they wish to do with approach and concept.



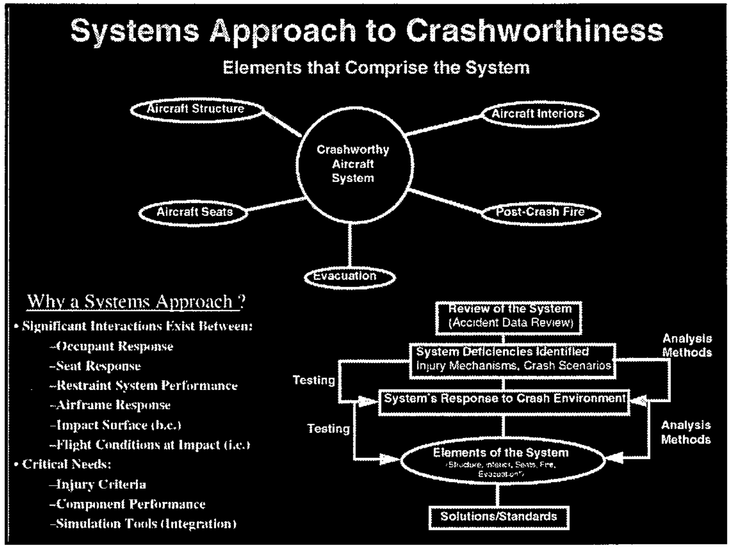
- In terms of Analytical Modeling and Simulation, Army personnel co-located at the facility are involved in an effort :

  To establish a standardized structural crash dynamics modeling and simulation capability from a single selected off-the-shelf computer code that can satisfy the need for a crashworthy performance and design evaluation tool.

- Several codes are being evaluated before a down-select with which an ACAP helicopter will be analyzed.
- Follow-on efforts will be to crash test an ACAP article (similar to one shown), compare the analytical/experimental results and make recommendations for code improvements as necessary.



- This effort is being well coordinated with various, intereted organization (see ovals above).
- The effort ties in well with helping to achieve the overall goal of the Human Survivability or Crashworthiness element in the NASA Aircraft Safety Program.



- **A Systems Approach to Crashworthiness to Enhance Human Survivability in aircraft has been emphasized in this presentation.**
- **If, as shown in the top circle, we want to have a crashworthy aircraft, all the elements that comprise that system must be considered as a system.**
- **Why ? Because (bottom left), interactions occur among all the elements that comprise the aircraft, structure, the seats, the restraints, the occupant, & the impact conditions.**
- **Thus (bottom right), a systematic approach of identifying the system, the scenarios, the response of the elements of the system, and using combined test and analysis methods are necessary to develop solutions and standards for designing crashworthy technology into aircraft for Enhancing Human Survivability.**

Concluding Remarks

- A Brief Review Was Given of the ASIST Process and Planning for NASA's New Aircraft Safety Program (ASP).
- During the ASIST Process, Against An Assessment of Expected Big Pay- off Areas for Reducing Fatalities and Serious Injuries In Fatal But Survivable Aircraft Accidents, The Human Survivability SubTeam :
  - Identified Four Major Focus Areas for Potential Investments Involving Survivability Initiatives.
  - Proposed A Priority List of Efforts and Allocations Within Areas.
- Planning (Both In Base and the Focused Program) Is Underway Which Supports Human Survivability Initiatives Involving Crashworthiness Technologies.
- *NASA LaRC Has Been and Still Is Involved With Aircraft Research to* Enhance Human Survivability Through Crashworthiness Technology.
- A Brief Review Was Given of Recent/Ongoing Crashworthiness Research at LaRC For Enhancing Human Survivability.
- Leveraging and Building on Existing Human Survivability Technology Efforts To Achieve The Aircraft Safety Program Goals Is a Strategy of The New NASA Program.

- **Concluding comments are listed above.**
- **Note that NASA Langley Research Center has been and still is involved with crashworthy technology which is aimed at enhancing human survivability.**
- **The new NASA Aircraft Safety Program element in Crashworthiness is leveraging and building upon these efforts as part of the program strategy.**

Improving Human Survivability In Aircraft Through Crashworthiness Technology

Huey D. Carden, Senior Researcher
Structures Division
Structural Mechanics Branch
NASA Langley Research Center
Hampton, VA. 23681-0001

Symposium on Enhancing Aircraft Survivability

A Vulnerability Perspective

Naval Post Graduate School
Monterey, CA
October 21-23, 1997

Outline of Presentation

- Introduction
- ASIST Process & NASA's New Aircraft Safety Program

  (Program Initiatives)
  - Accident Mitigation (Human Survivability Element)
  - *Accident Prevention*
  - *Aviation System -Wide Monitoring & Modeling*
- Review of Recent/On-Going Crashworthy Technology Activities at LaRC
- Concluding Remarks

Aviation Safety Research

"We will achieve a national goal of reducing the fatal aircraft accident rate by 80% within 10 years."

President William J. Clinton February 12, 1997

ASIST Process and Planning for NASA's New Aircraft Safety Program (ASP)

Aviation Safety Investment Strategy Team (ASIST)

Organization:

Tri-Lateral Group: NASA, FAA, DoD

NASA/FAA Coordinating Committee: Bob Whitehead, George Donohue, Guy Gardner,Chris Hart, Neil Planzer

Chair: Charlie Huettner

NASA Code R: Rich Christiansen, Lee Holcomb

FAA: Jan Brecht-Clark, Chuck Hedges, Ava Mims, Chris Seher

DoD: Don Dix

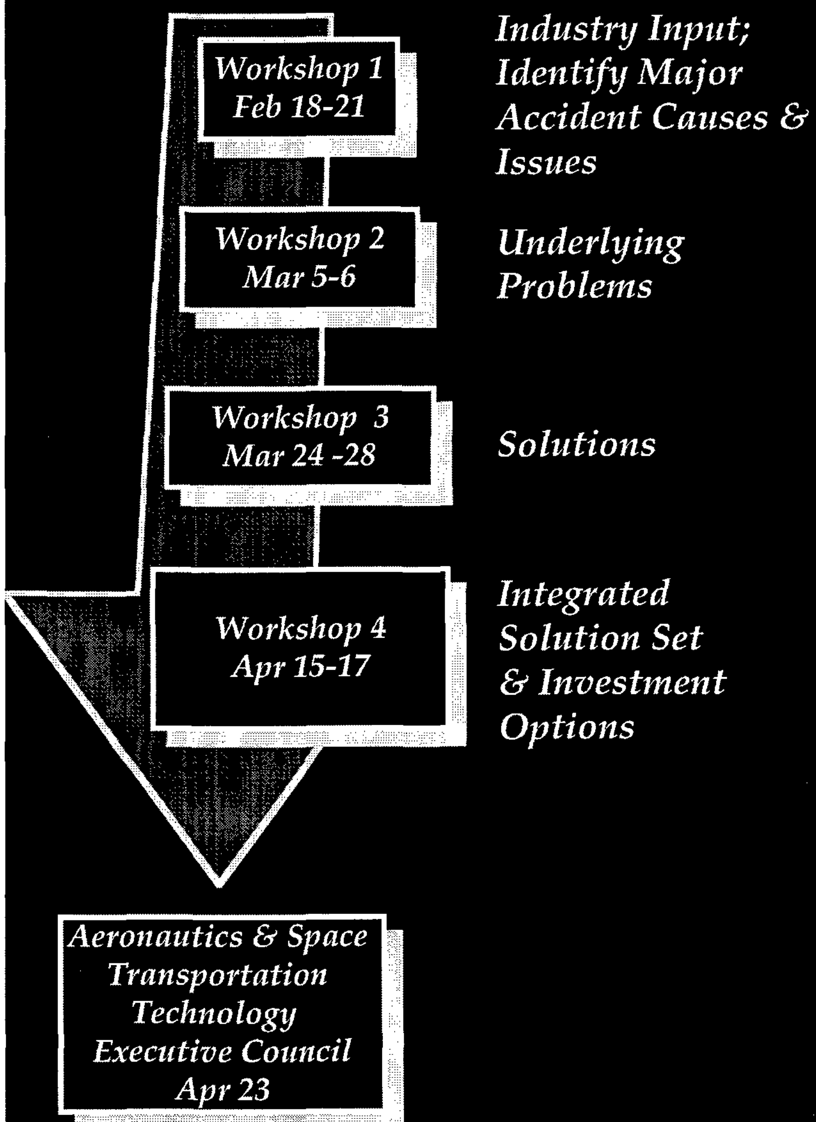
Weather Service: Julian Wright, Susan Zevin

Industry: NASA - AAC, FAA -RE&D Advisory Committee, ITLT

Sub-Team Focus Areas:

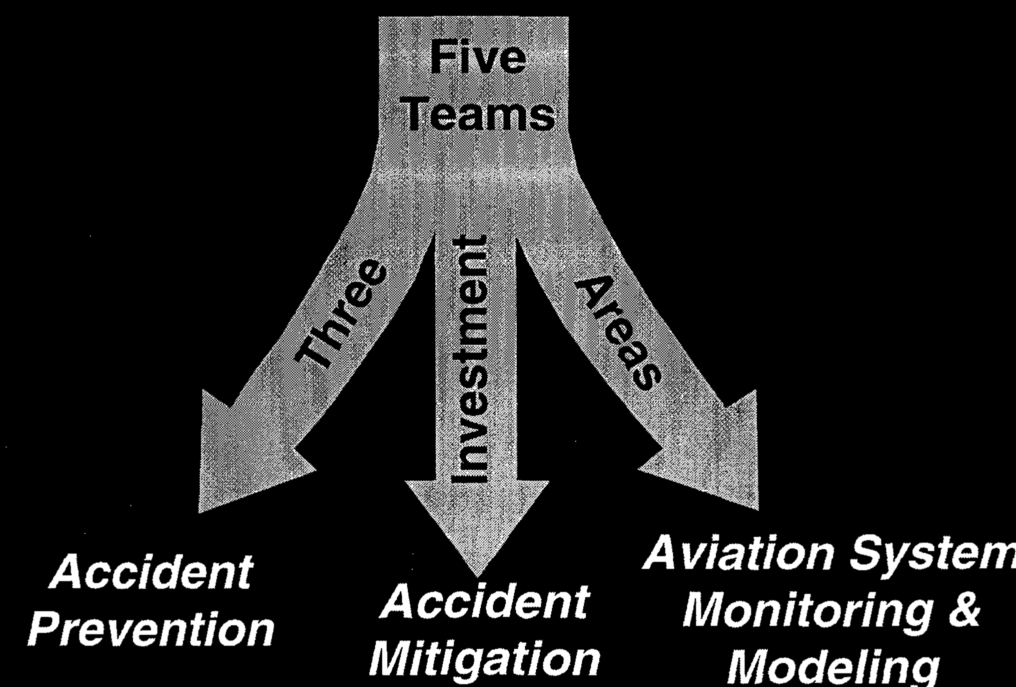
- » Human Error
- » Flight Critical Systems & Information Integrity
- » Weather
- » Aviation System-wide Monitoring, Modeling & Simulation
- » Human Survivability

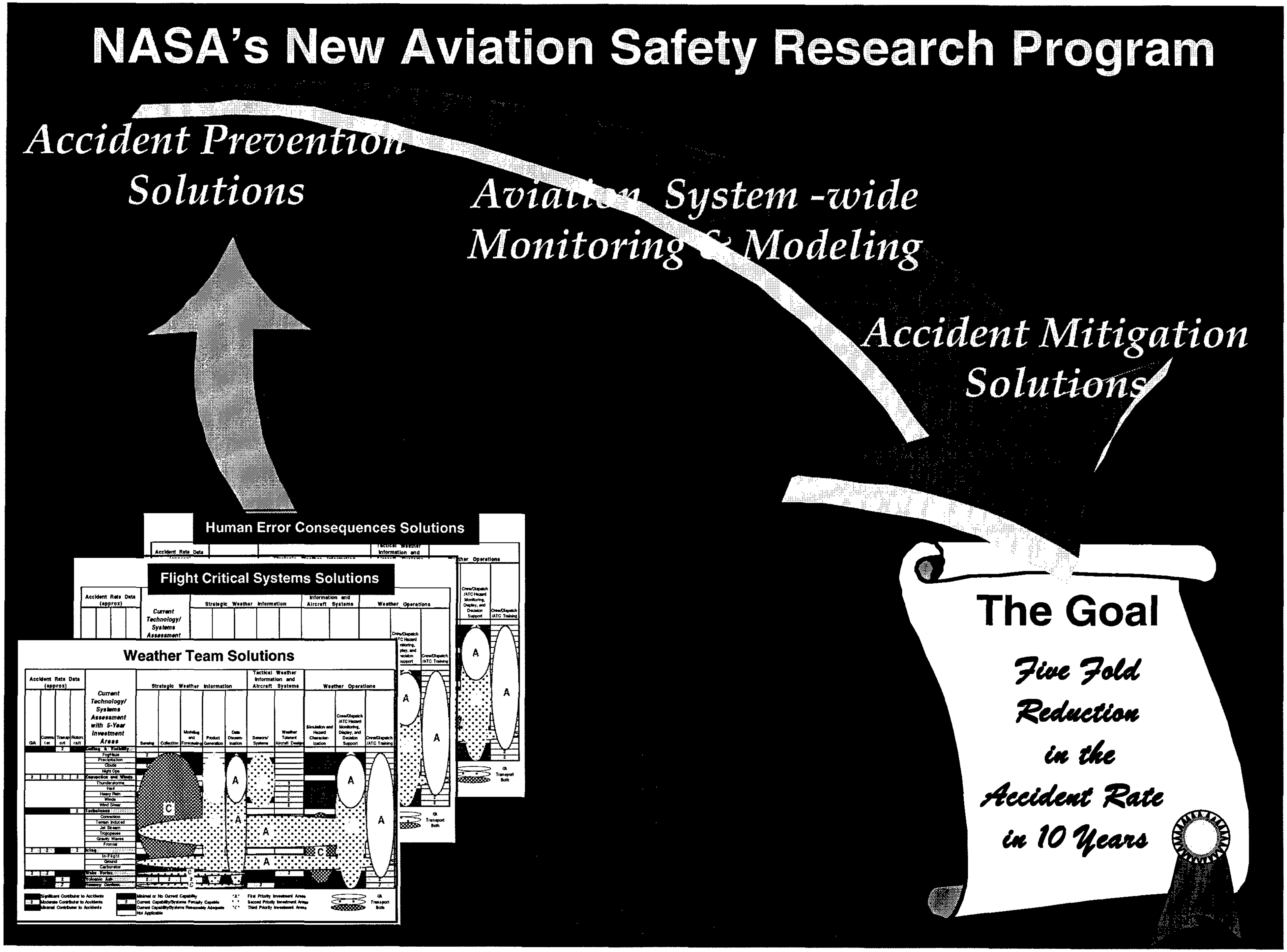
NASA Aviation Safety Investment Strategy Team (ASIST) Process

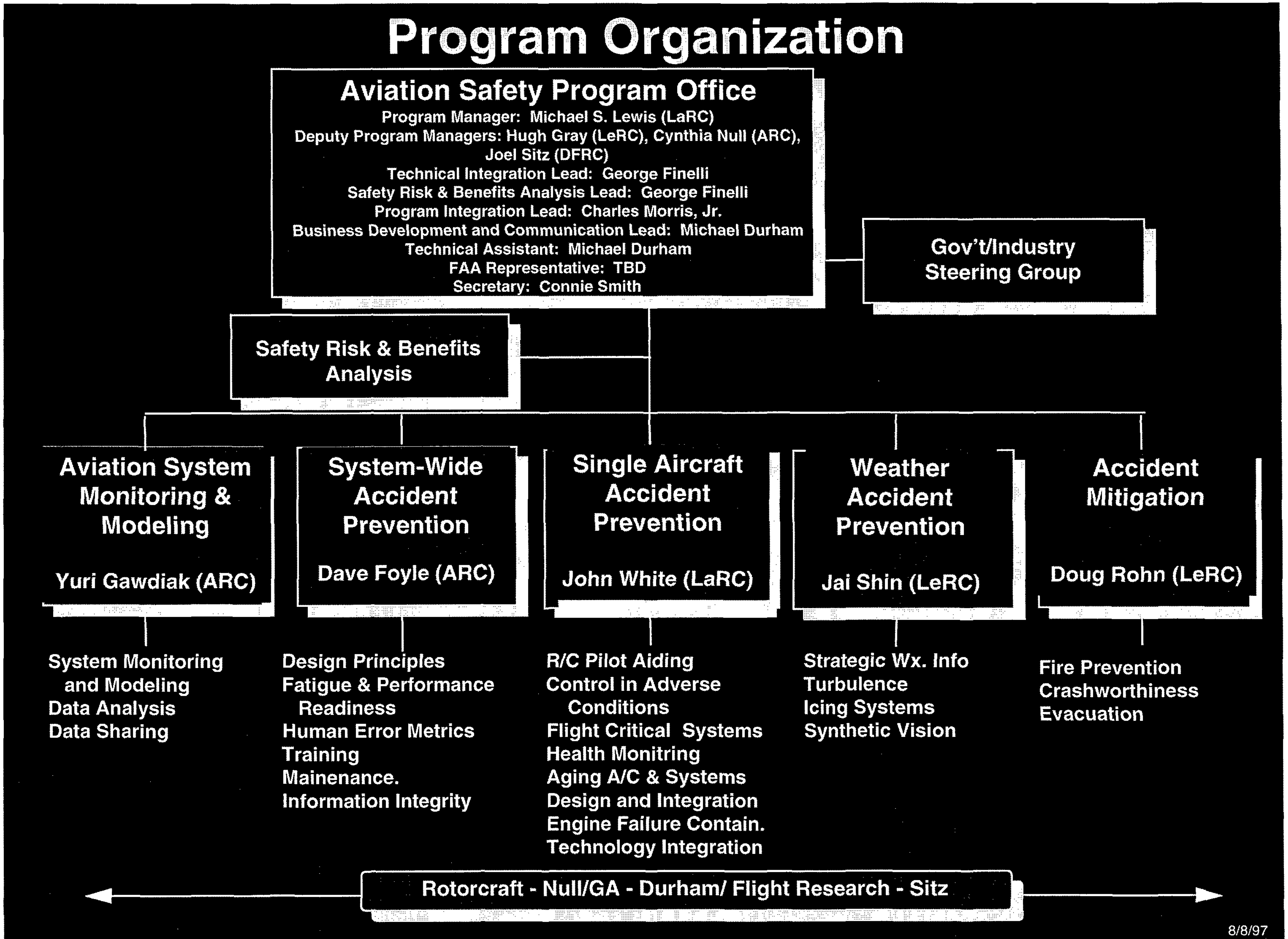


Five ASIST Sub-Teams Formed:

- Human Error Consequences
- Weather
- Flight Critical Systems & Information Integrity
- Human Survivability
- Aviation System-wide Monitoring, Modeling & Simulation




NASA's New Aviation Safety Research Program
Accident Prevention Solutions
Aviation System -wide Monitoring & Modeling
Accident Mitigation Solutions
Human Error Consequences Solutions
Flight Critical Systems Solutions
Weather Team Solutions
The Goal
Five Fold Reduction in the Accident Rate in 10 Years


Program Organization
Aviation Safety Program Office
Program Manager: Michael S. Lewis (LaRC)
Deputy Program Managers: Hugh Gray (LeRC), Cynthia Null (ARC), Joel Sitz (DFRC)
Technical Integration Lead: George Finelli
Safety Risk & Benefits Analysis Lead: George Finelli
Program Integration Lead: Charles Morris, Jr.
Business Development and Communication Lead: Michael Durham
Technical Assistant: Michael Durham
FAA Representative: TBD
Secretary: Connie Smith
Gov't/Industry Steering Group
Safety Risk & Benefits Analysis
Aviation System Monitoring & Modeling
Yuri Gawdiak (ARC)
System Monitoring and Modeling
Data Analysis
Data Sharing
System-Wide Accident Prevention
Dave Foyle (ARC)
Design Principles
Fatigue & Performance Readiness
Human Error Metrics
Training
Mainenance.
Information Integrity
Single Aircraft Accident Prevention
John White (LaRC)
R/C Pilot Aiding
Control in Adverse Conditions
Flight Critical Systems
Health Monitring
Aging A/C & Systems
Design and Integration
Engine Failure Contain.
Technology Integration
Weather Accident Prevention
Jai Shin (LeRC)
Strategic Wx. Info
Turbulence
Icing Systems
Synthetic Vision
Accident Mitigation
Doug Rohn (LeRC)
Fire Prevention
Crashworthiness
Evacuation
Rotorcraft - Null/GA - Durham/ Flight Research - Sitz
8/8/97

Human Survivability Team (In Time)
Attendance

Workshop 1-- February 19-21, 1997

Name	Organization
Huey Carden	NASA LaRC
LTC Bruce Bailey	DoD Army
Dr. James Hicks	DoD Army Safety Center
Van Gowdy	FAA/CAMI
Dick Hill	FAA Tech Center
Gus Sarkos	FAA Tech Center
Jerry Hordinsky	FAA/CAMI
Gary Frings	FAA-TC

Workshop 2 -- March 6 -7, 1997

Bill Shook	Douglas Aircraft
Mike Norman	McDonnell Douglas
George Neat	DOT Volpe Center
Ron Welding	ATA
Jim Hicks	Army Safety Center
Huey Carden	NASA LaRC
Mike Downs	FAA/ACE
Jeff Marcus	FAA/CAMI
Jerry Hordinsky	FAA/CAMI
Gary Frings	FAA-TC

Workshop 3 -- March 24 -28, 1997

Diane Sandwick	Boeing Payloads
Todd Curtis	Boeing Airplane Safety Eng.
Bill Shook	Douglas Aircraft Cabin Safety
Steve Hooper	WSU-NIAR
George Neat	DOT Volpe Center
Ronda Ruderman	Assn. of Flight Attendants
RaNae Contarino	NAWC Pax
Gregory Feith	NTSB-DCA
Huey Carden	NASA LRC
Jeff Marcus	FAA/CAMI

Workshop 3 -- March 24 -28, 1997

Name	Organization
Stephen Soltis	FAA Resource Specialist
Gary Frings	FAA-TC
Robert Friedman	NASA LeRC

Workshop 4 -- April 15-17,1997

Name	Organization
Bruce Holmberg	ARCCA
Christopher Witkowski	Assoc. Flight Attendants
Maynard M. Foster	Assoc. Flight Attendants
Dr. Jonathan Kaufman	DoD NAWCAD
Paul Kinzay	DoD Naval Safety Center
Ric Loeslien	DoD NAWCAD
RaNae Contarino	DoDNAWCADPax
Martin Lentz	DoD UASF-WL/FIVS
George Neat	DOT/Vople Center
Gary Frings	FAA TC
Jeff Marcus	FAA/CAMI
Jerry Hordinsky	FAA/CAMI
Bill Shook	McDonnell Douglas
Huey Carden	NASA LaRC
Howard Ross	NASA LeRC
David Myres	NAVMAR
Maria Thorpe	NAWCAD Pax
Matt McCormick	NTSB

Human Survivability (HS)

Goal:

- The Human Survivability Sub-Team Seeks To Identify, Support, and Develop Solutions To Safety Issues That Can Mitigate and Significantly Reduce The Number of Fatalities and Serious Injuries in Fatal But Survivable Accidents.

Relation To Other Sub-Team Goals:

Commonalties

- Classes of Vehicles Cover General Aviation, Rotorcraft, and Transport.
- Current Assessments of Issues Are Statistically-Driven As Possible.
- Future Assessments Are To Be Scenario-Driven For Future Eras.

Differences:

- The Objective and Metric of the Human Survivability Sub-Team Are the Substantial Reduction of the Number of Fatalities and Serious Injuries, Independent of Fatal Accidents.
- While a Reduction in Fatal Accident Rate Almost Guarantees a Reduction in Absolute Fatality Numbers, The Converse Is Not Necessarily True.
- Fatality Reduction Is Highly Desirable, But Unless Significant "No Fatality" Accidents Results The Fatal Accident Rate May Be Larger Than Desired.

Human Survivability

Accident Statistics And Expert Advice Were Used To Guide Planning Efforts And Priority In Human Survivability

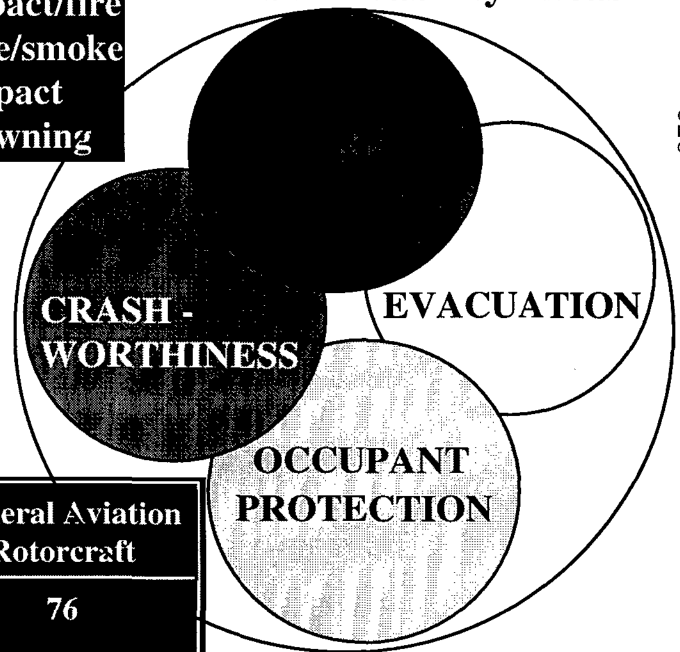
Aircraft Category →	Transport World Wide 82-94(14 yr)	Transport World Wide 82-94 (14 yr)
Fatal Accident Area	Number of Accidents	OnBoard Fatalities
Landing	173	290
On-Ground Fire	93	1082
ATC Com.	61	2111
Maint. & Insp.	58	1560
CFIT	49	2890
Loss of Control	45	2632
Ground Ops	33	162
Engine/Crew	21	346
Approach	20	1257
TakeOff Conf.	13	243
Inflight Fire	12	673
Uncontained Engine	13	199

1959-90

Accident Data Show:

52% Nonsurvivable	50% Impact/fire
3% 1-3 survivors	27% Fire/smoke
45% survivable	18% Impact
	5% Drowning

Interrelated Human Survivability Areas



1985-1995

Aircraft Category →	General Aviation-All	General Aviation Rotorcraft
Fatal with at least one survivor	701	76
Accidents with fire	2624	194
Fatal Accidents with fire	1588	101
Total Fatal Accidents	4979	359

+ Additional Data Mining

+ Expert(s) Advice

Human Survivability (HS)

Challenges/Objective of HS Investments

- Challenges/Objective of Fire Investment :

  To Identify, Support, and Develop Fire Prevention, Detection, and Suppression Concepts That Can Minimize Fire Hazards in Crashes and In-Flight Incidents.

- Challenges/Objective of Crashworthiness Investment:

  To Develop A Systems Approach To Crashworthiness Design That Includes Validated Analysis Methodology, New Structural Concepts And Materials, Safer Cabin Interiors Design, Advanced Restraint Equipment, Design And Injury Criteria To Enhance Crash Safety.

- Challenges/Objective of Evacuation Investment :

  To Develop A Systems Approach For Evacuation That Includes Analysis/ Simulation Methodology, New Procedures ,Training, Equipment, And Design Criteria Which Can Enhance And Provide Means For More Timely Evacuation During Fire In Aircraft Accidents.

- Challenges/Objective of Occupant Protection Investment:

  To Develop Detection/Warning Means, New Procedures ,Training, And Equipment Which Can Provide Occupant Protection From Fire Related Hazards And Thus Provide Additional Evacuation Time.

All the Challenges/Objectives Are Aimed At Mitigation/Reduction of Fatalities and Serious Injuries In Current As Well As New Aircraft Configurations.

Human Survivability (HS)

Prioritization Of Investment Areas Across The Major Four Human Survivability Issues

1. Fire Prevention (Pre/Post Incident)
   - Crash Resistant Fuel Systems
   - Fire Safe Fuels/Systems
   - Fire Detection/Suppression
   - Fire Safe Materials
2. Systems Approach To Crashworthiness
   - Analytical Modeling
   - Metal/Composite Structures
   - Design Criteria/Guidelines
   - Biomechanics
3. *Systems Approach To Evacuation* *
   - *Modeling*
   - *Procedures/Training*
   - *Equipment*
   - *Exit/Slide Design Criteria*
   - *Guidelines*
4. *(Occupant Protection) Maintaining Physiological Stability**
   - *Alternate Ox Generation*
   - *Protection from Contaminants*
   - *Hypoxia*

** Currently UnFunded in ASP*

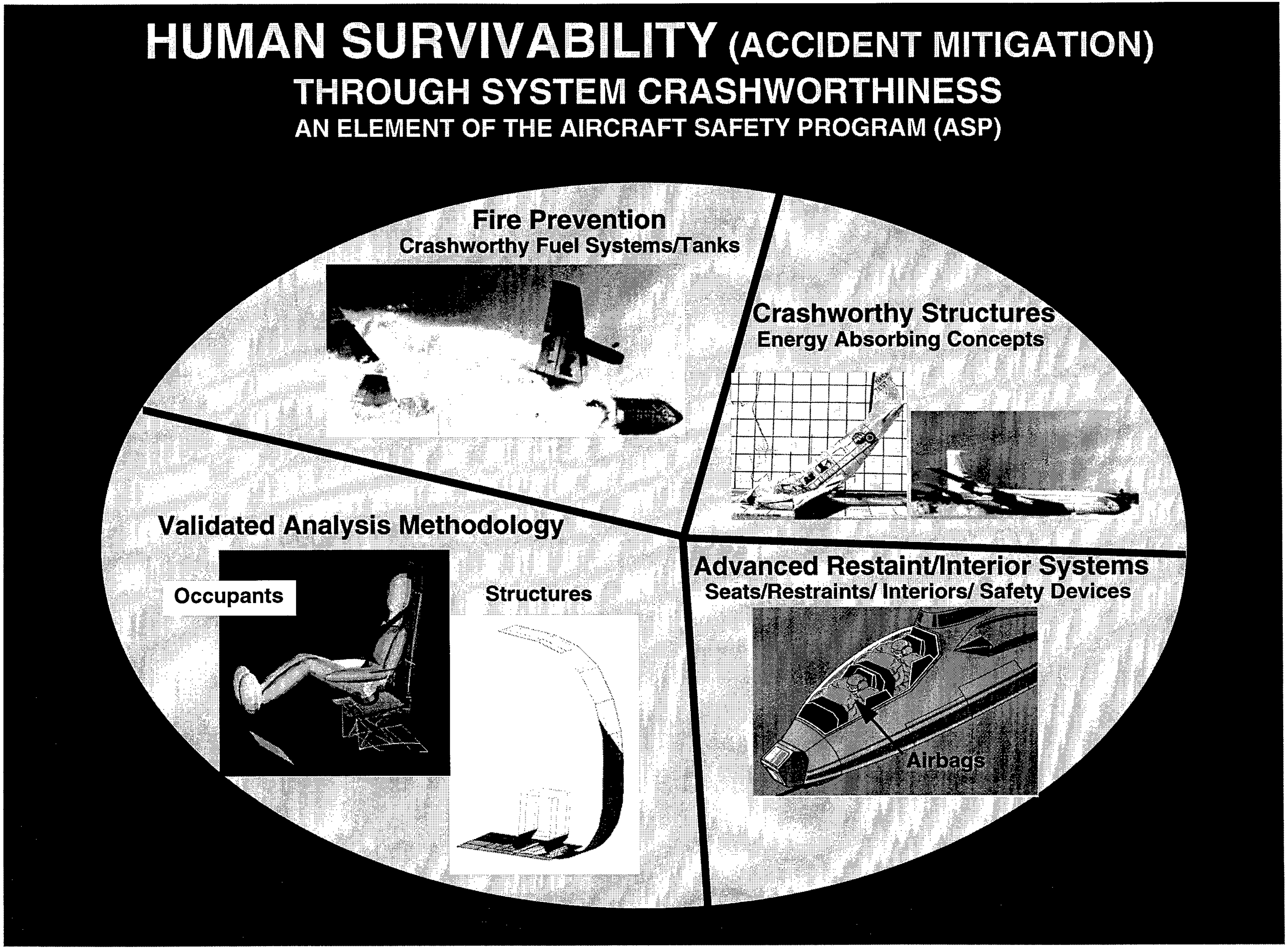
Planning Workshops

Near Term Timeline

- Industry Brief 8/97
- Detailed Planning Workshops 9/97-12/97
- Early Activities Initiated 10/97 - 12/97
- Prepare/Issue NASA Research Announcement (or equivalent) - 11/97-2/98
- Proposals Due - 1/98 - 3/98
- Proposals Reviewed - 2/98 - 5/98
- New Starts Initiated 4/98 - 10/98

Initial Workshop Subjects

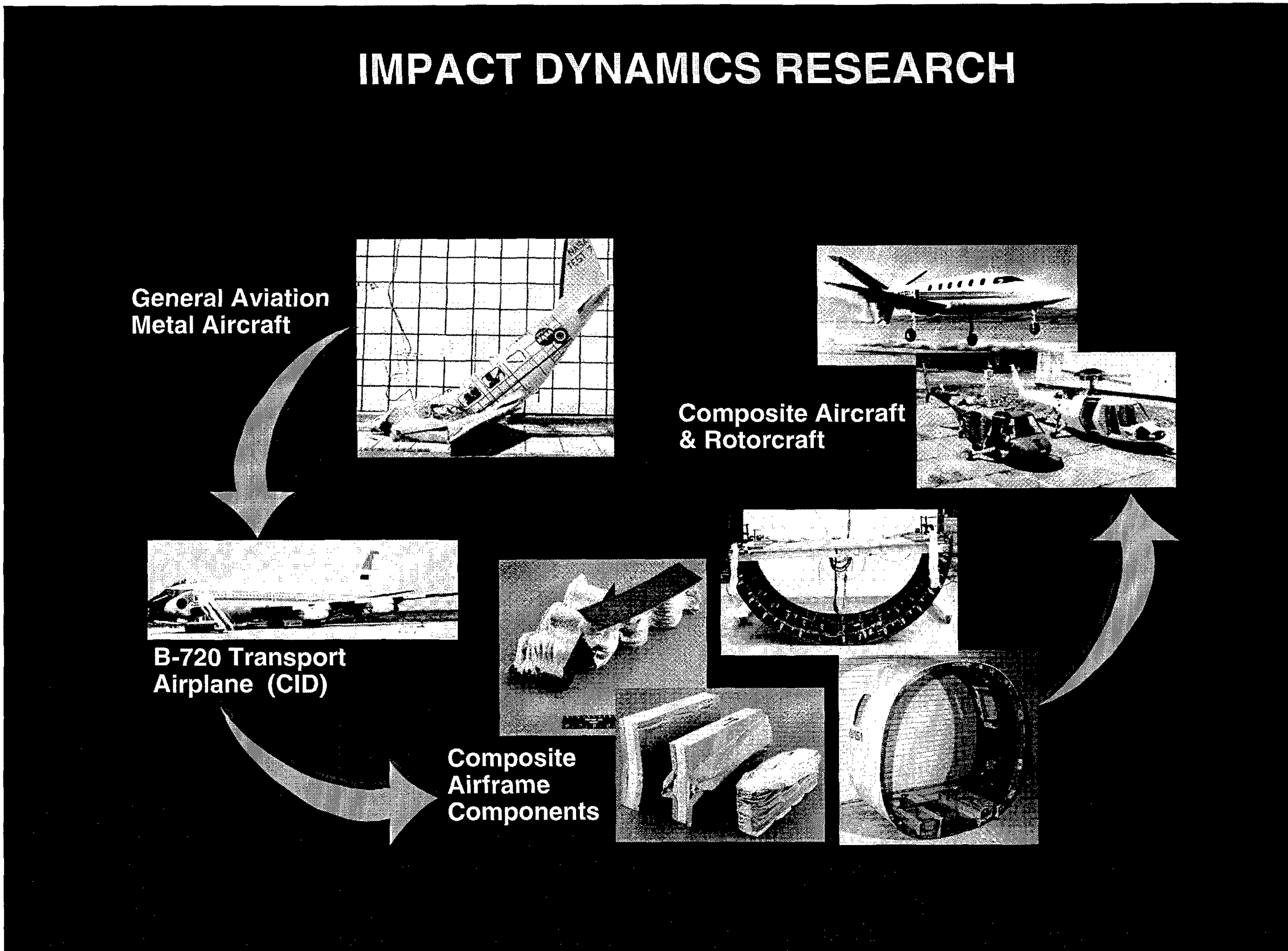
- Data Analysis/Data Monitoring Data Sharing
- Health Monitoring
- Strategic Weather Information
- Aging Aircraft/Systems
- **Fire Prevention (July-Dec)**
- **Crashworthiness (July-Dec)**
- Synthetic Vision
- Rotorcraft Pilot Aiding
- Training
- Control in Adverse Conditions
- Information Integrity
- Flight Critical Systems
- Human Error

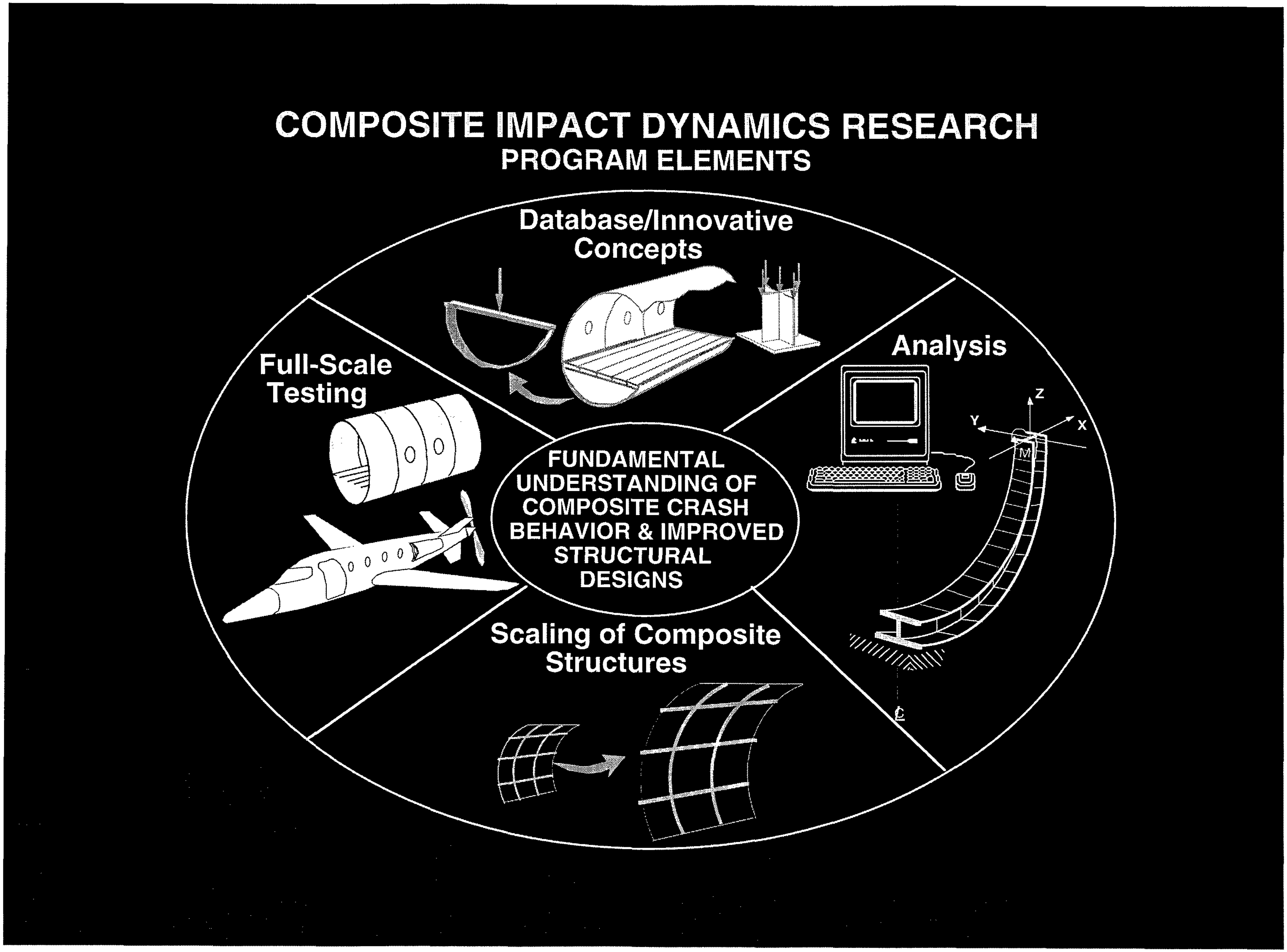

HUMAN SURVIVABILITY (ACCIDENT MITIGATION)
THROUGH SYSTEM CRASHWORTHINESS
AN ELEMENT OF THE AIRCRAFT SAFETY PROGRAM (ASP)
Fire Prevention
Crashworthy Fuel Systems/Tanks
Crashworthy Structures
Energy Absorbing Concepts
Validated Analysis Methodology
Occupants
Structures
Advanced Restaint/Interior Systems
Seats/Restraints/ Interiors/ Safety Devices
Airbags

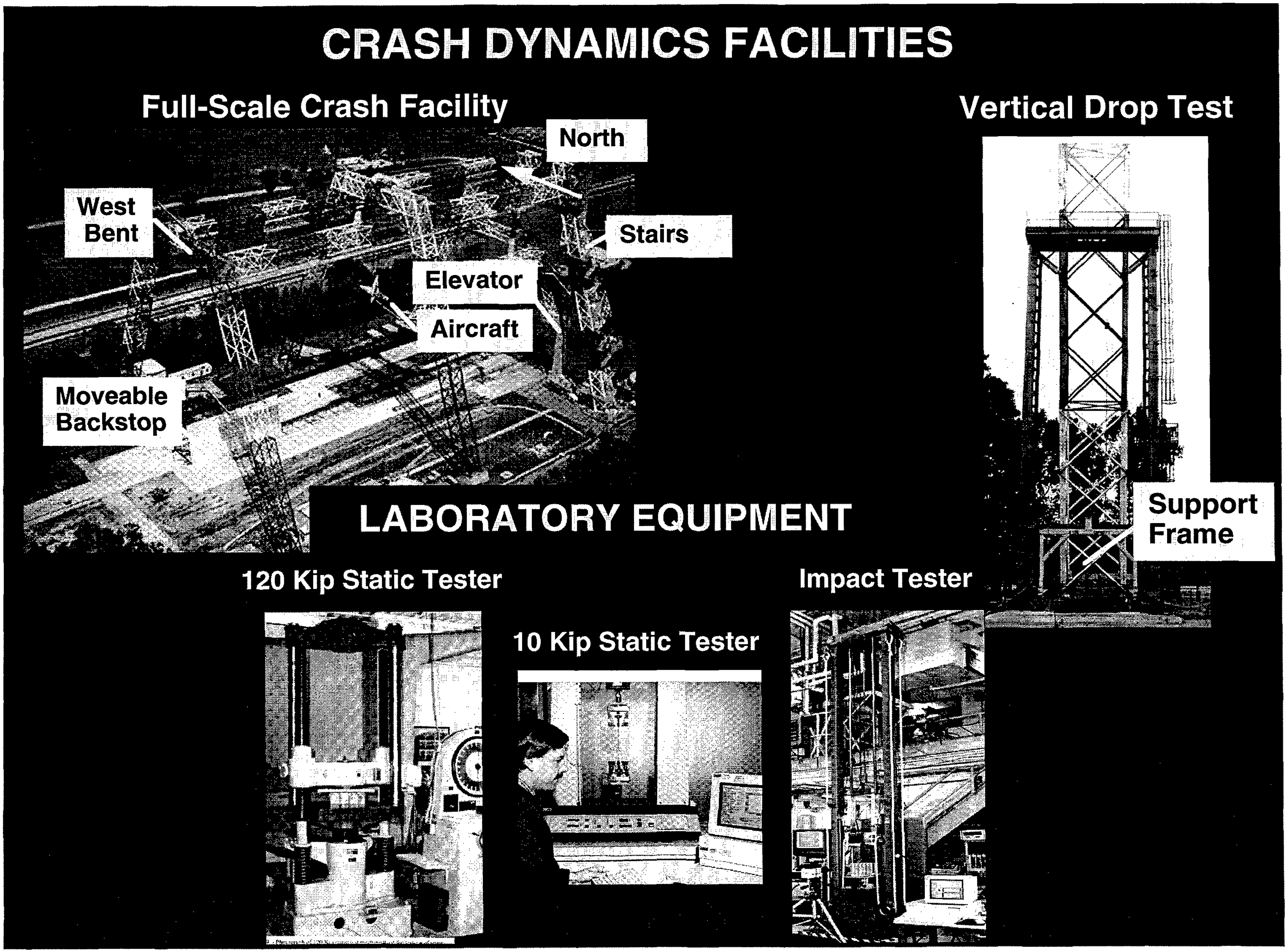
At This Point I'd Like to Turn To Examples of Some Recent/Ongoing Research at LaRC Directly Related to the Crashworthy Technology Areas in NASA's New Aircraft Safety Program (ASP)

History of Crashworthiness

	1960's	1970's	1980's	1990's	2000+
NASA		- 33 GA Aircraft Crash Tests at IDRF - Initiate Development of DYCAST	- Initiate Composite Crash Dynamics Research - CID - DYNA3D Code for Crash Analysis	- Crash Tests of Composite Lear Fan, Terry (Cirrus), & Starship Aircrafts - AGATE Program - Refinement of DYCAST	- ASP
Military	- Army Crash Mishap Studies	- MIL-STD-1290 - Crash Survival Design Guide - KRASH - Crashworthy Fuel Systems - Crash Test of CH-47	- Crash Testing of UH-60, AH-64, SH-60 - Crash of Comp. ACAP Helicopter - Wire Strike Protection System	- STO on Crash Analysis - Water Impact - Airbag Technology -Refinement of KRASH	


IMPACT DYNAMICS RESEARCH
General Aviation Metal Aircraft
B-720 Transport Airplane (CID)
Composite Airframe Components
Composite Aircraft & Rotorcraft


COMPOSITE IMPACT DYNAMICS RESEARCH
PROGRAM ELEMENTS
Database/Innovative Concepts
Full-Scale Testing
Analysis
Z
Y
X
M
FUNDAMENTAL UNDERSTANDING OF COMPOSITE CRASH BEHAVIOR & IMPROVED STRUCTURAL DESIGNS
Scaling of Composite Structures


CRASH DYNAMICS FACILITIES
Full-Scale Crash Facility
North
West Bent
Stairs
Elevator
Aircraft
Moveable Backstop
Vertical Drop Test
Support Frame
LABORATORY EQUIPMENT
120 Kip Static Tester
10 Kip Static Tester
Impact Tester

HUMAN SURVIVABILITY REQUIREMENTS

- MAINTAIN SURVIVABLE VOLUME
  - FUSELAGE CAGE
- RESTRAIN OCCUPANT WITHIN SURVIVABLE VOLUME
  - STANDARD RESTRAINTS
  - INFLATABLE RESTRAINTS
  - PRETENSIONERS
- LIMIT OCCUPANT LOADS
  - ENERGY ABSORBING SEATS
  - ENERGY ABSORBING SUBFLOORS
  - ANTI-PLOWING FUSELAGE STRUCTURES
  - LOAD LIMITERS & PRETENSIONERS
- MITIGATE POST-CRASH HAZARDS
  - Evacuation
  - Fire
  - Water

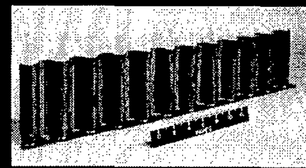
ENERGY ABSORBING BEAM STUDIES

OBJECTIVES

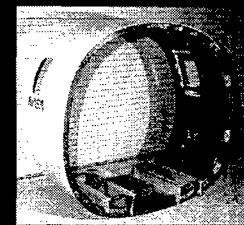
- Design and Test Energy-Absorbing Beam Concepts For Composite Aircraft Subfloors
  - Retain integrity of flange for seat attachment
  - Retain some post crush structural integrity and stiffness
  - Produce acceptable loads transmitted to seat/occupants
  - Be readily manufactured and inexpensive as possible.
- Eventually *Retrofit* a Concept Into a Composite Airplane for Full-Scale Crash Evaluation

APPROACH

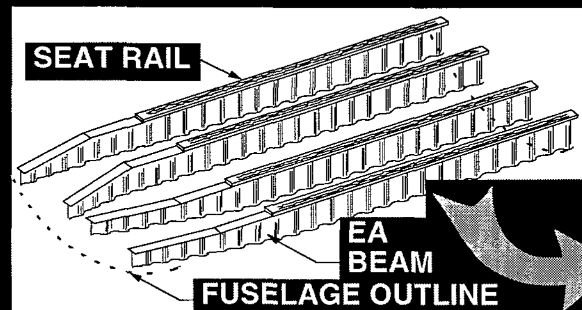
EA BEAMS



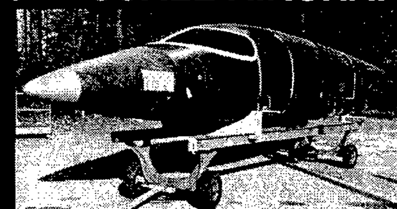
FUSELAGE SECTION



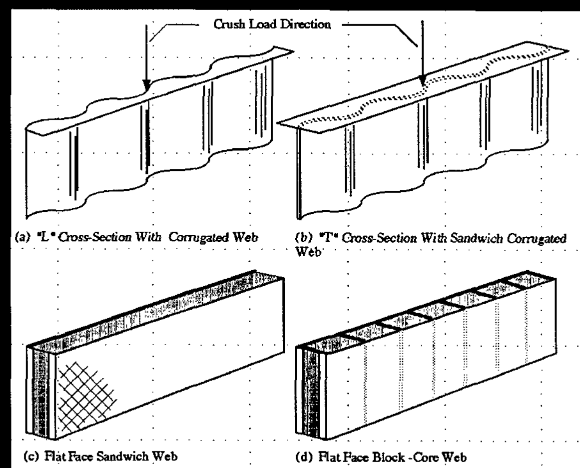
SCHEMATIC OF EA FLOOR



FULL-SCALE AIRCRAFT

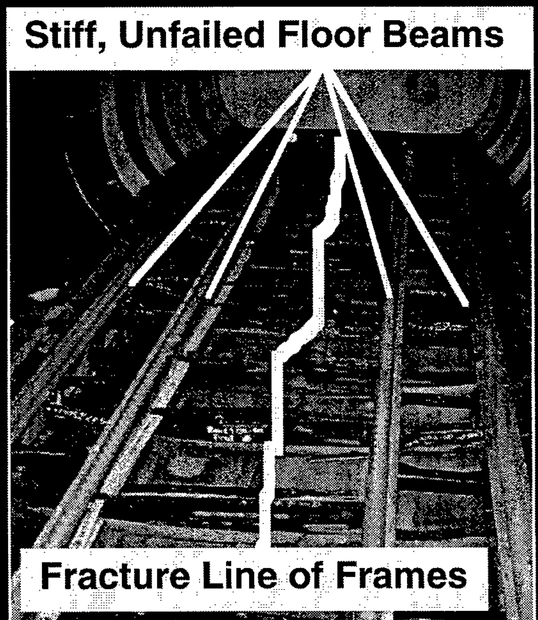


BEAM CONCEPTS

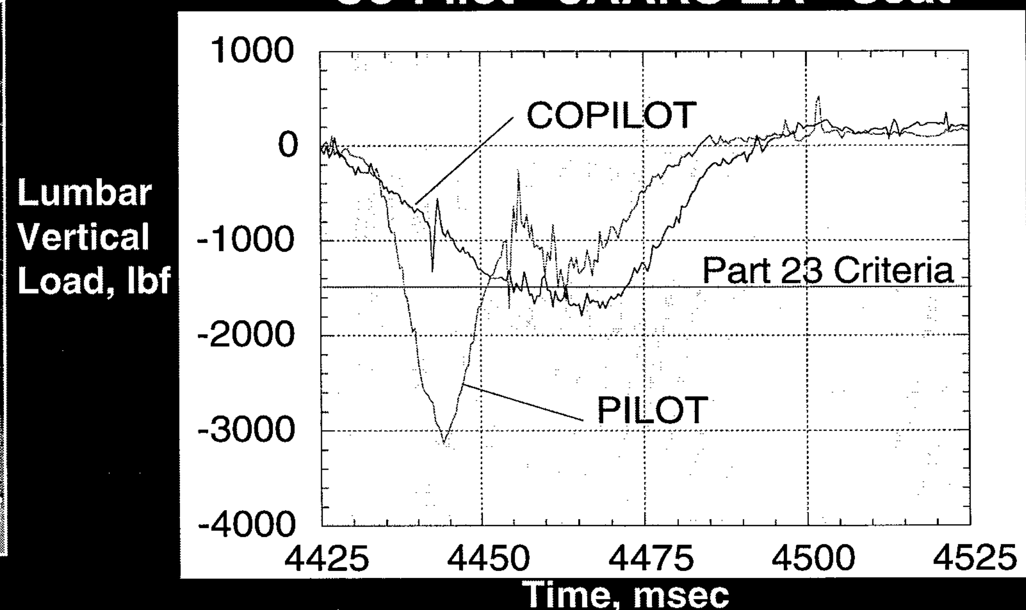


(a) "L" Cross-Section With Corrugated Web
(b) "T" Cross-Section With Sandwich Corrugated Web
(c) Flat Face Sandwich Web
(d) Flat Face Block-Core Web

LEAR FAN COMPOSITE AIRCRAFT CRASH TEST PROVIDES IMPORTANT DATA ON STRUCTURE AND OCCUPANT LOADS



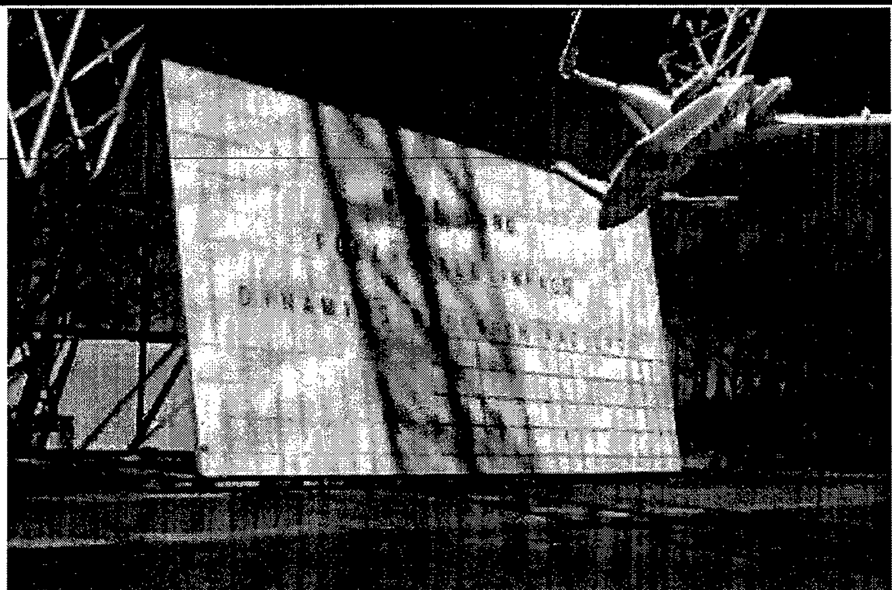
Pilot - Standard Non - EA Seat
Co-Pilot - JAARS EA - Seat

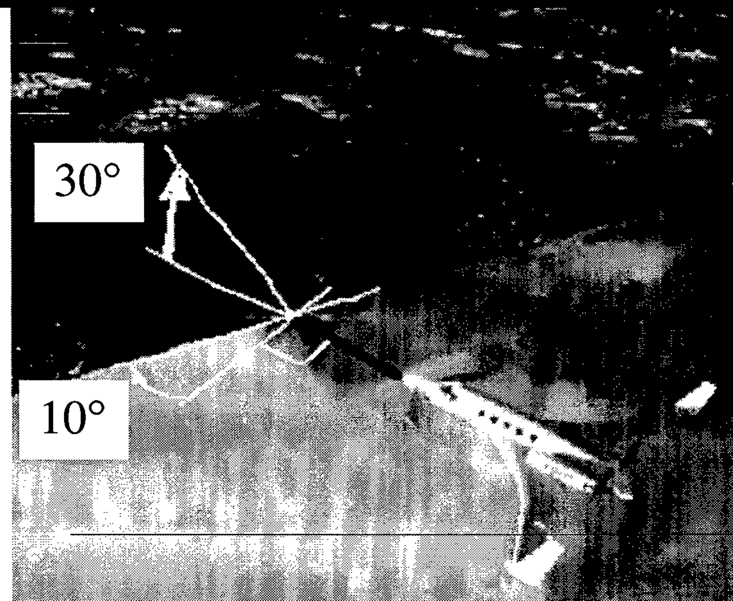


Composite Aircraft Crash Test at LaRC

Objectives:

- Add to Database of Information For Crash Behavior of Composite Aircraft Specimens (Honeycomb vs Skin-Frames)
- Specifically, Generate and Maximize Visual & Measured Crash Loads & Behavior Data for Structure, Seats, & Occupants of a Composite Aircraft During a Single Test Comprised of :
  - An Initial Impact Which Produces Primarily Vertical Loads at Part 23 Requirement of 27 fps Impact Velocity With Emphasis of Test Being Evaluation of Performance of Structure, Standard (Non-Energy Absorbing) Seats, and EA Seats, AND
  - A Secondary Impact To Produce Primarily Longitudinal Loads at Part 23 Requirement of 42 fps Velocity, With 10° Yaw on Seat/Occupants With Emphasis for Evaluation of Performance of Airbag Technology





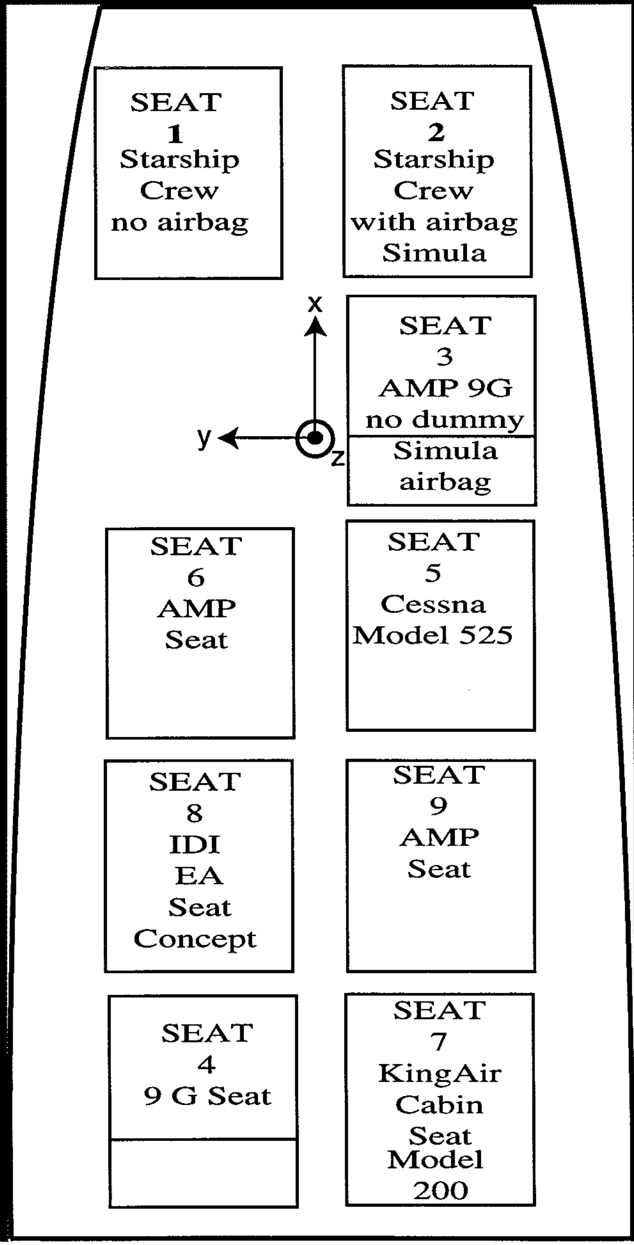
Test Parameters--Initial Vertical Impact -- Near to Prior Conditions for Comparison (Honeycomb vs Skin-Frame)

HorizontalVelocity	= 84 fps
Vertical Velocity	= 27 fps
Flight Path Angle (FPA)	= - 18°
Pitch Angle (Relative to FPA)	= 18°
Yaw & Roll Angles	= 0.0°

Test Parameters Secondary Longitudinal Impact

Horizontal Velocity	= 42 fps
Vertical Velocity	= 0.0 fps
Flight Path Angle (FPA)	= - 30°
Pitch & Roll Angle	= 0.0°
Yaw Angle	= 10°

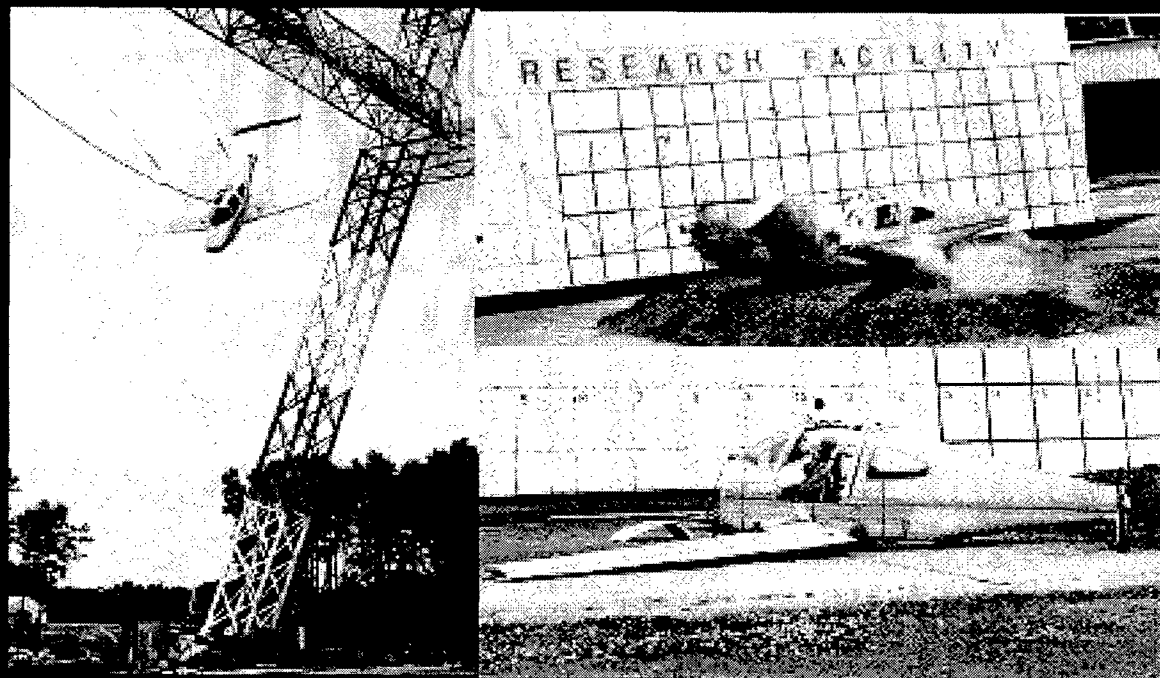
Interior Arrangement of Seats/Experiments and Typical Seat/Occupant Dummy in StarShip



Intelligent Dummy Data Acquisition System (IDDAS) Self-Contained Instr-umentation (Such as shown below) was part of the data acquisition system.

Occupant dummy is in standard GA seat.

Terry Engineering Full-Scale Testing



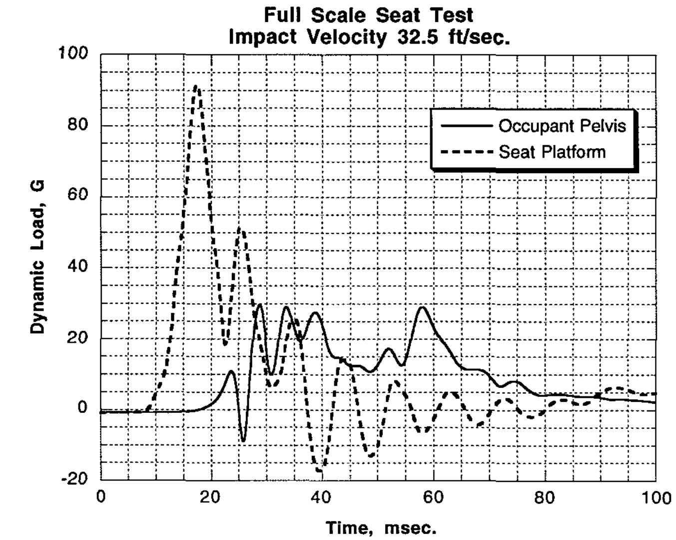
- **Series of 4 full-scale tests**
  - 2 tests on concrete
  - 2 tests on soft soil
- **SBIR contract effort-** Data to be presented by Principal Investigator to ID&M

- **Objectives** - Systems approach to crashworthiness
  - Prevention of soil scooping
  - Improved energy absorbing seats/cushion
  - Improved restraint systems (airbags & harnesses)
  - Improved structural energy absorption and integrity

Excellent Occupant Crash Protection Achieved With an Energy Absorbing Concept Developed for "Thrush" Aircraft Seat (Ayres Corporation's Agriculture Airplane)

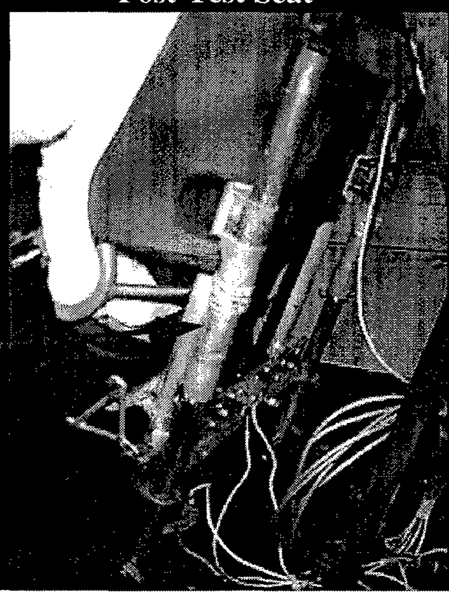
Pre-Test Seat

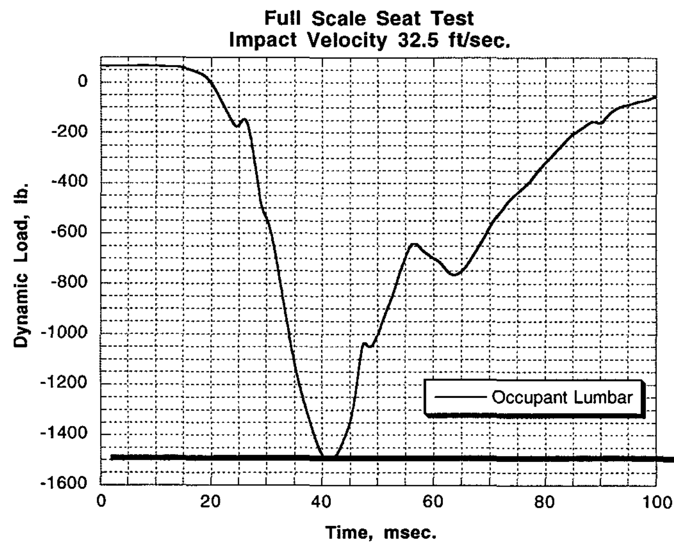
EA Concept



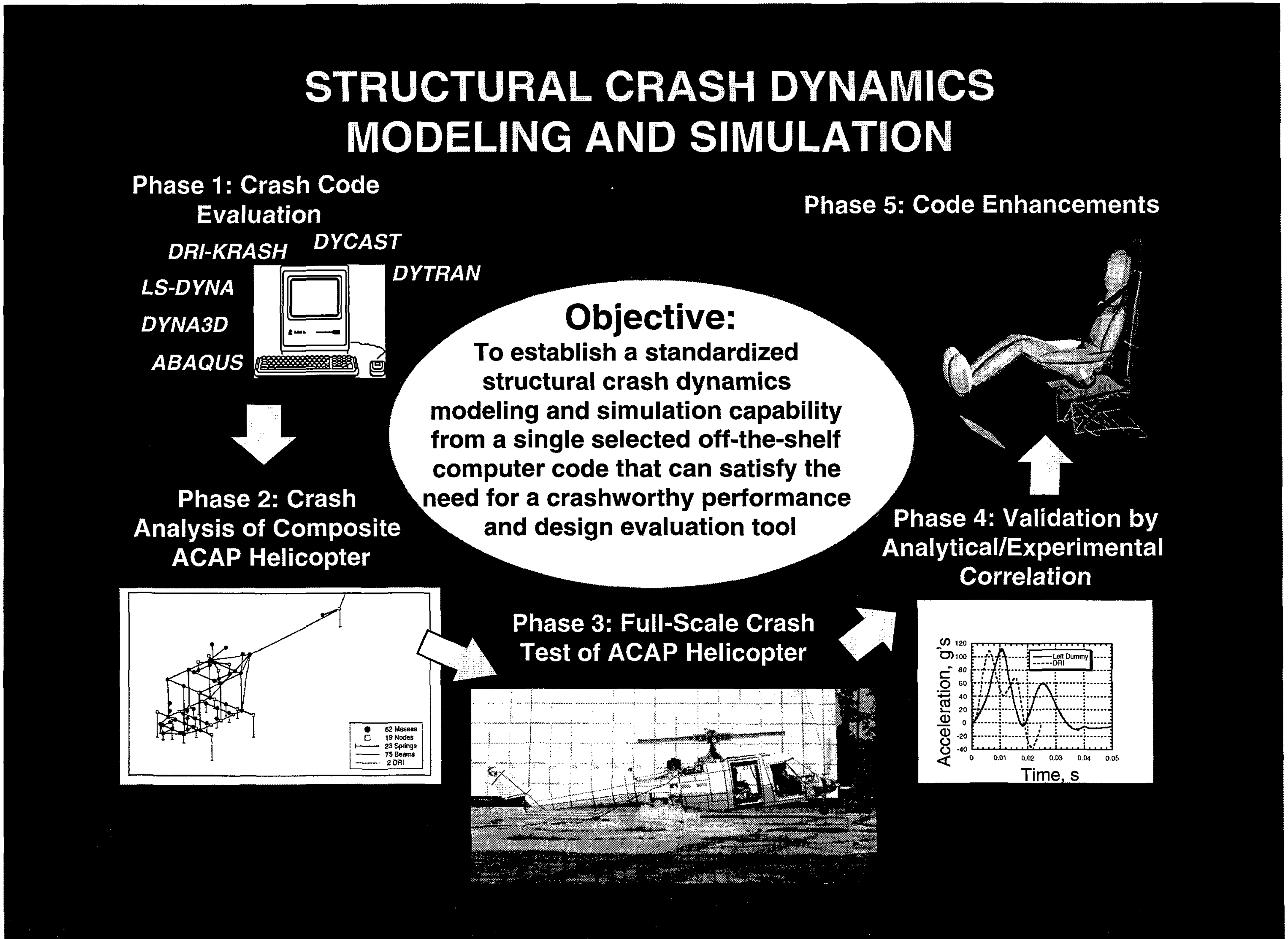
Post-Test Seat

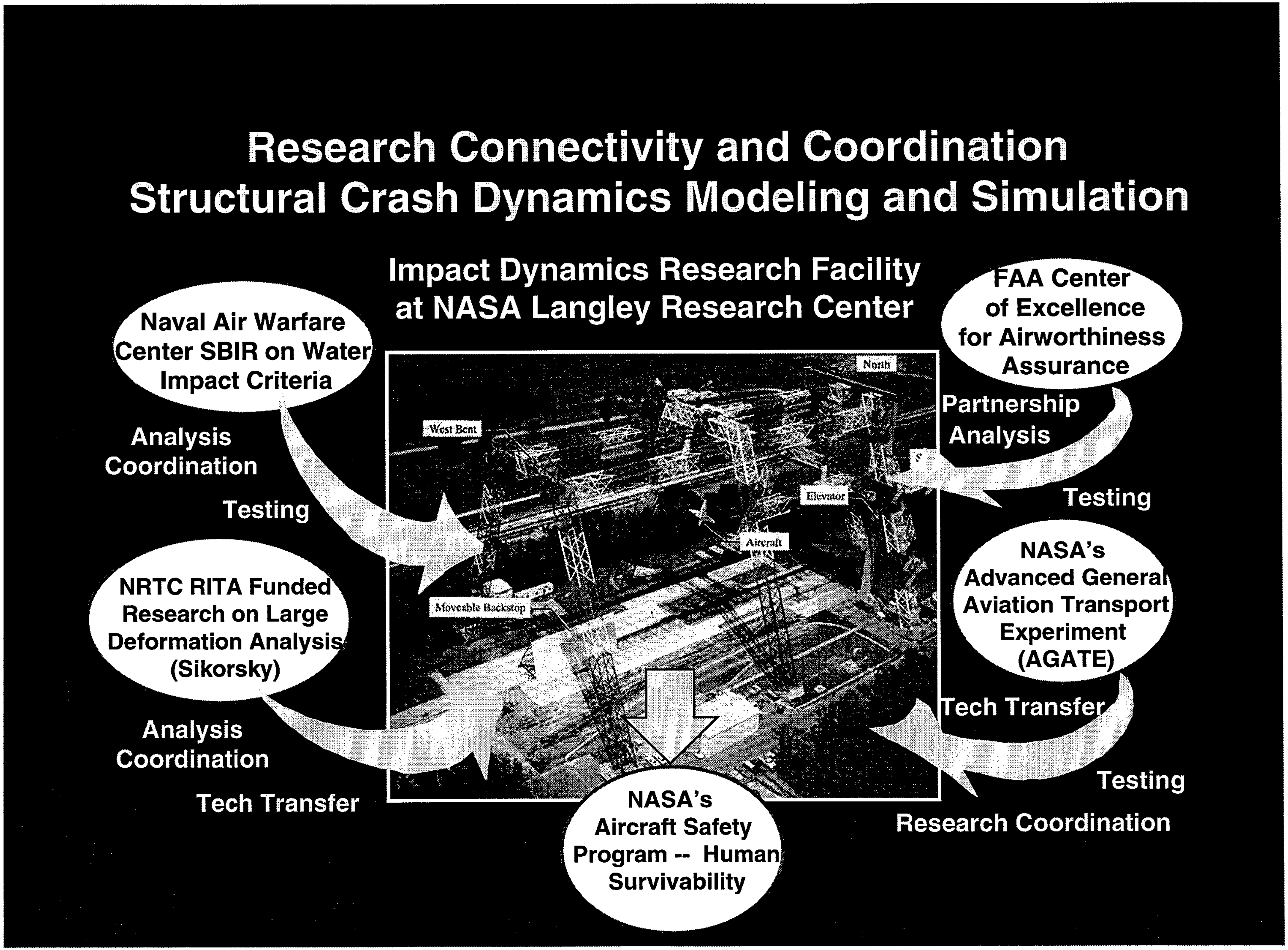
Stroked EA Concept





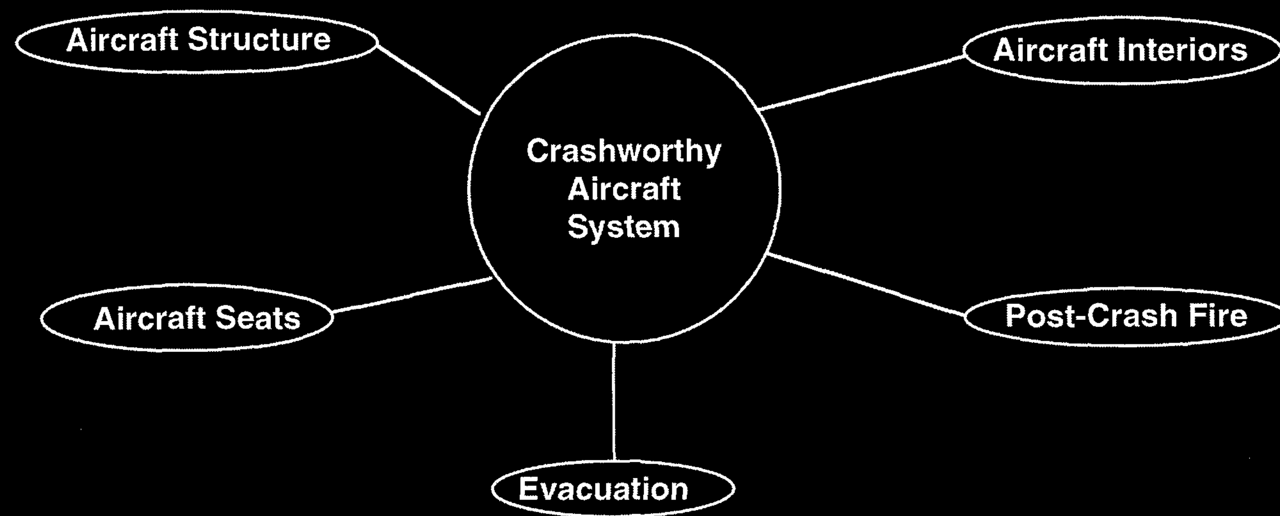
1500 lbf
Spinal Limit
(Part 23 Reg.)


STRUCTURAL CRASH DYNAMICS
MODELING AND SIMULATION
Phase 1: Crash Code Evaluation
DRI-KRASH
DYCAST
DYTRAN
LS-DYNA
DYNA3D
ABAQUS
Objective:
To establish a standardized structural crash dynamics modeling and simulation capability from a single selected off-the-shelf computer code that can satisfy the need for a crashworthy performance and design evaluation tool
Phase 2: Crash Analysis of Composite ACAP Helicopter
52 Masses
19 Nodes
23 Springs
75 Beams
2 DRI
Phase 3: Full-Scale Crash Test of ACAP Helicopter
Phase 4: Validation by Analytical/Experimental Correlation
Acceleration, g's
Time, s
Left Dummy
DRI
Phase 5: Code Enhancements


Research Connectivity and Coordination
Structural Crash Dynamics Modeling and Simulation
Impact Dynamics Research Facility
at NASA Langley Research Center
Naval Air Warfare Center SBIR on Water Impact Criteria
Analysis Coordination
Testing
NRTC RITA Funded Research on Large Deformation Analysis (Sikorsky)
Analysis Coordination
Tech Transfer
West Bent
North
Elevator
Aircraft
Moveable Backstop
FAA Center of Excellence for Airworthiness Assurance
Partnership Analysis
Testing
NASA's Advanced General Aviation Transport Experiment (AGATE)
Tech Transfer
Testing
Research Coordination
NASA's Aircraft Safety Program -- Human Survivability

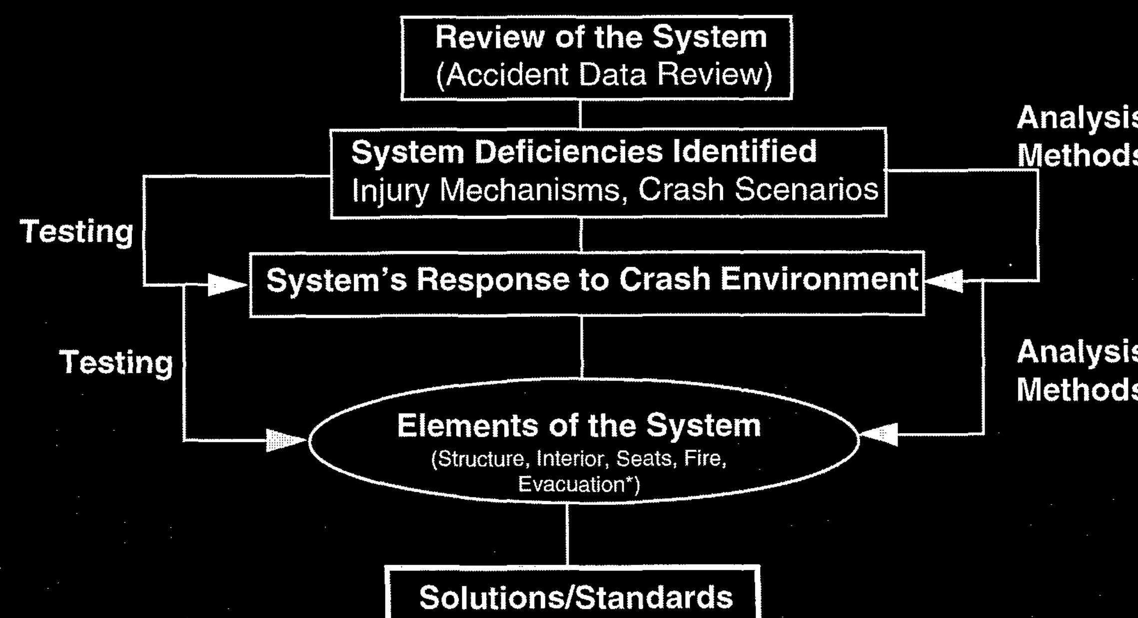
Systems Approach to Crashworthiness

Elements that Comprise the System



Why a Systems Approach ?

- Significant Interactions Exist Between:
  - –Occupant Response
  - –Seat Response
  - –Restraint System Performance
  - –Airframe Response
  - –Impact Surface (b.c.)
  - –Flight Conditions at Impact (i.c.)
- Critical Needs:
  - –Injury Criteria
  - –Component Performance
  - –Simulation Tools (Integration)



Concluding Remarks

- A Brief Review Was Given of the ASIST Process and Planning for NASA's New Aircraft Safety Program (ASP).
- During the ASIST Process, Against An Assessment of Expected Big Pay- off Areas for Reducing Fatalities and Serious Injuries In Fatal But Survivable Aircraft Accidents, The Human Survivability SubTeam :
  - Identified Four Major Focus Areas for Potential Investments Involving Survivability Initiatives.
  - Proposed A Priority List of Efforts and Allocations Within Areas.
- Planning (Both In Base and the Focused Program) Is Underway Which Supports Human Survivability Initiatives Involving Crashworthiness Technologies.
- NASA LaRC Has Been and Still Is Involved With Aircraft Research to Enhance Human Survivability Through Crashworthiness Technology.
- A Brief Review Was Given of Recent/Ongoing Crashworthiness Research at LaRC For Enhancing Human Survivability.
- Leveraging and Building on Existing Human Survivability Technology Efforts To Achieve The Aircraft Safety Program Goals Is a Strategy of The New NASA Program.

U.S. Department
of Transportation
**Federal Aviation
Administration**

Technical Center

Atlantic City Int'l Airport
New Jersey 08405

OCT 21 1997

Defense Technical Information Center
ATTN: DTIC-OCP
8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, VA 22060-6218

Mr. Thomas H. Minnich
Dear Mr. Minnich:

At the recent Aircraft Survivability/A Vulnerability Perspective Symposium in Monterey, I made a presentation entitled "Fire Safety Improvements Through R&D". I do not have a paper that exactly coincides with my presentation. However, I have enclosed three published papers, which constitute the majority of my presentation. Obviously, these papers were previously approved for publication by the Federal Aviation Administration, where I am employed.

I have also enclosed a release form authorizing unlimited distribution.

Sincerely yours,

Gus Sarkos

Constantine P. Sarkos
Manager, Fire Safety Section

WATER SPRAY SYSTEM DEVELOPMENT AND EVALUATION FOR ENHANCED POSTCRASH FIRE SURVIVABILITY AND IN-FLIGHT PROTECTION IN CARGO COMPARTMENTS

Timothy R. Marker
Constantine P. Sarkos
Richard G. Hill
Fire Safety Section
Federal Aviation Administration
William J. Hughes Technical Center
Building 287 AAR-422
Atlantic City International Airport, NJ 08405
USA

1. SUMMA⌃Y
This paper describes full-scale fire tests conducted by the Federal Aviation Administration (FAA) to evaluate and optimize water spray systems in two specific aircraft fire safety applications. The first application was an onboard cabin water spray system designed to improve postcrash fire survivability. The goal is to suppress a severe cabin fire, initiated by a large external fuel fire, in order to improve the available time for passenger evacuation. The second application was a cargo compartment water spray system for the purpose of suppressing and controlling in-flight cargo/luggage fires. In this case, the water spray system must suppress and contain a worst-case, deep-seated fire for as long as 180 minutes, or until an airplane can be safely landed.

2. INTRODUCTION
Although aircraft crashes occur very infrequently, the life safety consequences of a postcrash fire are of great concern because of the potential involvment of large quantities of flamr᠆ıble jet fuel, the use of polmeric materials to line ..nd furnish the cabin, and the problems associated with the rapid evacuation of a large number of passengers from a confined environment.

The goal of enhanced postcrash fire survivability is twofold: (1) additional available time for passenger evacuation by reducing cabin fire hazards, and (2) greater evacuation rate of passengers. Improvements in postcrash fire safety attaining these goals have been achieved in recent years (Sarkos, 1989), including the installation of more fire resistant cabin materials, based on stringent fire test standards developed and adopted by FAA. The FAA has strived to develop further improvements in postcrash fire survivability in a joint program with the United Kingdom (U.K.) Civil Aviation Authority and Transport Canada to develop an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the U.K. by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consisted of a large number of small nozzles, mounted throughout the ceiling, which discharged a fine water spray (mean droplet diameter of about 100 microns) throughout the length of the cabin for a period of 3 minutes (Whitfield, et al, 1988).

The test arrangement for the cabin water spray tests simulated a survivable aircraft crash involving fuselage exposure to an external fuel fire. The fire source was an 8-by-10 foot pan of burning jet fuel which had been shown previously to be representative of the thermal threat created by a large fuel spill fire. The discussion in this paper will be limited to a typical scenario comprised of a fuel fire adjacent to an opening (simulated rupture) in the test fuselage the size of Type A door (76 by 42 inches). A variable speed exhaust fan in the front of the fuselage created a draft inside the cabin, allowing the degree of fuel fire penetration through the hole and the resultant severity of the fire inside the cabin to be varied. Good control over the fuel fire conditions were maintained because the tests were conducted inside a building, assuring test repeatability. The 8-by-10 foot pan fire tests were conducted with both a narrow-body fuselage and a wide-body fuselage. The former is a surplus B-707 airplane while the latter is a 130-foot-long hybrid consisting of a 40-foot DC-10 section married to a 90-foot cylinder. Similar tests with a smaller fuel fire were conducted in a Metroliner commuter aircraft test article.

Aircraft cargo compartments are protected with Halon 1301 total flooding fire suppression systems. Since the production of halon ceased in developed countries on January 1, 1994, as specified by an international agreement called the Montreal Protocol, the future availability of halon for aviation is uncertain. Therefore, the FAA has a program to evaluate replacement and alternative agents/systems, such as water spray, in cargo compartment and other aircraft applications for the purpose of developing certification criteria for those agents deemed acceptable (FAA, 1993). A cargo compartment water spray system could also trade-off the weight penalty associated with a cabin water spray system.

The cargo compartment water spray tests were conducted in the lower forward compartment of the wide-body test article. The volume of the cargo compartment was 2300 cubic feet and the leakage rate was 85 cubic feet per minute, or one air change every 27 minutes.

3. EFFECTIVENESS OF CABIN CONTINUOUS WATER SPRAY SYSTEM

Narrow-Body Test Article. A plan view of the narrow-body test article is shown in figure 1, indicating the fuel pan location, continuous (SAVE) water spray system nozzle arrangement and location of instrumentation and cabin materials. The water spray system consisted of 120 nozzles which discharged 72 gallons of water over a period of 3 minutes. Instrumentation consisted of thermocouples, smoke meters, gas analyzers, gas sampling equipment, calorimeters, and photographic and video cameras. A 24-foot-long section of the test article, centered at the external fire pan, was outfitted with 5 rows of passenger seats, ceiling panels, stowage bins, sidewalls, and carpet. All materials were compliant with the current FAA fire test standards (Sarkos, 1989). A similar test setup was utilized in the wide body tests described later in the paper.

Initially, a zero ambient wind condition was simulated by not operating the exhaust fan. With the absence of flame penetration through the fuselage opening, the fire exposure of cabin materials was dominated by intense thermal radiation. The results of the zero wind tests, with and without water spray, are shown in figure 2. The shaded areas in this and subsequent figures show the range in measurements at a particular fuselage station. In all cases, the highest readings were at the highest locations, and the readings decreased the closer the measurement location was to the floor. Temperature was measured at 1-foot increments from a location 7 feet high (slightly below the ceiling) to a location 1 foot above the floor. Smoke was measured at three heights: 5 feet, 6 inches; 3 feet, 6 inches; and 1 foot, 6 inches. All gas measurements were at 5 feet, 6 inches and 3 feet, 6 inches.

Figure 2 exhibits a rapid rise in temperature and toxic gas production and a decrease in oxygen concentration at approximately 5 minutes in the test without water spray. This behavior indicates the development of a flashover condition at 5 minutes. However, when water spray was used, survivable conditions prevailed for the entire 7-minute test duration. The time interval of actual water spray discharge was from 15 seconds until approximately 195-200 seconds into the test. Therefore, in addition to the reduction in cabin fire hazards during the water spray discharge, there were notable improvements in the cabin environment after the discharge was completed.

Survival time was calculated from the measured hazards by employing a fractional effective dose (FED) model (Speitel, 1995). It assumes that the effect of heat and each toxic gas on incapacitation is additive and that the increased respiratory rate due to elevated carbon dioxide levels is manifested by enhanced uptake of other gases. The FED plot in figure 2 shows incapacitation occurred at 5 minutes without water spray discharge, corresponding to the time of flashover. Discharge of water spray prevented flashover within the 7-minute test duration and maintained a survivable environment within that increment (FED<0.1 at 7 minutes). Therefore, the increase in survivability provided by water spray discharge was much greater than 2 minutes.

A "moderate" wind scenario was devised, by operating the exhaust fan to induce fuel fire flame penetration through the fuselage opening, in order to create a more severe fire threat than imposed by the zero wind condition. Figure 3 shows the results of those test. The profiles are quite similar to the zero wind test (figure 2) but are transposed earlier in time by about 2 minutes. Flashover occurred between 150 and 180 seconds without water spray. With water spray, flashover occurred much later (about 300 seconds) and with less intensity (lower temperature rise and gas production). The FED plot shows that the increase in survival time was 215 seconds. Figure 3 also shows that water spray is highly effective in removing water soluble acid gases such as hydrogen fluoride.

The water spray system was also evaluated against a "high" wind scenario. In this case, the fuel fire flames penetrated across the ceiling practically to the opposite side of the cabin. The fire was so severe that it overwhelmed the water spray, and it became necessary to terminate the test after only 60 seconds. The high wind test further illustrated that the benefits of fire safety design improvements are highly dependent upon the fire scenario, and for some very severe scenarios it is virtually impossible to improve survivability by design changes.

Wide-Body Test Article. In the wide-body test article, the SAVE system consisted of 324 nozzles, arranged in 5 rows along the length of the fuselage. A quantity of 195 gallons of water was discharged over a period of 3 minutes. A "moderate" wind condition, causing fuel fire flame penetration through the fuselage opening, was utilized to evaluate the effectiveness of water spray in the wide-body test article. Figure 4 shows the result of those tests. As in the narrow-body tests, significant reduction in cabin temperatures and toxic gas levels were evidenced during the water spray test. Of some concern is the light transmission profiles reflecting the reduction in visibility due to smoke. For more than half the test duration, because the water spray tends to lower the ceiling smoke layer, there is a greater reduction in light transmission while the water is being discharged. Apparently, the amount of smoke particulate removal or "washing out" by the water spray is more than offset by the lowering of the smoke layer. Later, however, the

reduction in light transmission with an unabated fire becomes more significant.

The FED curve indicates a loss of survivability at 215 seconds without the water spray system. Examination of the temperature and gas levels. particularly oxygen concentration (not shown), indicates the onset of flashover at about 210 seconds. With water spray, flashover was prevented over the 5-minute test duration and the cabin environment (away from the fire source) remained survivable. On the basis of the FED calculation, the improvement in survival time at the end of the test was 85 seconds, and would likely have been considerably longer, perhaps 2-3 minutes, had the test not been terminated.

4. OPTIMIZATION OF CABIN WATER SPRAY SYSTEM

Because of payload, weight penalty is an overriding consideration in aircraft design. The weight penalty associated with the SAVE system is somewhat excessive, if not prohibitive. The concept of a zoned system divides an airplane cabin into a series of water spray zones. Discharge of water within each zone is independent of the other zones and triggered by a sensor within the zone. In this matter the quantity of water discharged is dictated by the presence and spread of fire, eliminating the ineffectual and wasteful discharge of water away from the fire as in the SAVE system (Marker, 1991). A zoned system was designed, tested and optimized in the narrow body test article.

Each zone was 8 feet in cabin length. Four spray nozzles were mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed toward the center of the zone. Based on preliminary tests, a temperature of 300 degrees Farenheight (F) was selected to manually activate water discharge. The temperature was measured at the center of the zone about 6 inches below the ceiling . Three types of nozzles were evaluated; low, 0.23 gallons per minute (gpm) (SAVE nozzle); medium, 0.35 gpm; and high, 0.50 gpm. A more severe simulated wind condition than employed previously was used as the test condition.

The calculated FED profiles from the initial series of optimization tests are shown in figure 5. The SAVE water spray system, discharging 72 gallons of water, increased the survival time by 110 seconds. More importantly, the medium and high flow rate nozzles, discharging a total of only 24 gallons of water, increased the survival time beyond the SAVE system by about 55 seconds and 35 seconds, respectively. The improvement provided by the higher flow rate nozzles is apparently due to the application of larger quantities of water where it is needed most -- in the immediate fire area. An interesting result is that the medium flow rate nozzles provided more protection than the high flow rate nozzles. A possible explanation is that the discharge time was longer with the medium flow rate nozzles; i.e., 180 seconds versus 140 seconds.

In an attempt to optimize the zoned system, 9 zoned water spray tests were conducted, employing 4 water quantities and 3 nozzle flow rates. The results are summarized in figure 6 in terms of the additional available escape time beyond the baseline test without water discharge. The results of the SAVE test are also shown (108 seconds additional escape time). Each of the zoned tests provided a significant improvement in the additional escape time, which was greater than the improvement with the SAVE system in 5 of the 9 cases. Even with only 4 gallons of water, the zoned system was effective, increasing the available escape time by 53 seconds. The optimal nozzle discharge rate was 0.35 gpm.

In order to optimize the water quantity, the efficiency of a water spray system was defined as the ratio of the additional available escape time (seconds) to the quantity of water discharged (gallons), or seconds per gallons (SPG). Figure 7 compares SPG for the various water spray configurations on the basis of nozzle flow rate. It is evident that the most efficient or optimum zoned system utilized a medium flow rate nozzle (0.35 gpm) and a water quantity of 8 gallons. The optimum zoned water spray system (SPG = 20.4) was a factor of 13.6 more efficient than the continuous waters spray system (SPG = 1.5). It is significant that as much as 20 seconds of additional available escape time per gallon of water discharged may be achieved by a water spray system, operating effectively in a postcrash fire environment, where each second of available escape time is critical.

Improved visibility is another advantage of a zoned water spray system since continuously discharging water throughout the airplane tends to lower the ceiling smoke layer. With the zoned system the disruption of the smoke layer is primarily confined to the spray zones. Visibility during the zoned system tests improved by approximately 40-50 seconds compared to the SAVE system test (figure 8).

5. EFFECTIVENESS OF ZONED CABIN WATER SPRAY SYSTEM

<u>Wide-Body Test Article</u>. The effectiveness of a zoned water spray system was examined in the wide-body test article. The placement of nozzles was similar to the narrow-body arrangement with two exceptions. First, there were six nozzles in each of the two boundary planes. Second, for some tests a half-zoned geometry was used; i.e., the zone extended to the cabin symmetry plane rather than across the full cabin width. Another variation in some tests was the spray discharge activation temperature. As in the narrow-body tests, initial activation of spray discharge was set at 300 degrees F; however, subsequent zone activation's were delayed until the temperature reached 500 degrees F. This was done with the aim of conserving water for application in the initial zone where the fire intensity was greatest. The total quantity of water was only 21

gallons (vs. 195 gallons with the SAVE system). This was calculated by scaling to the optimum zone system and SAVE system water quantities in the narrow-body test article.

The calculated FED profiles are shown in figure 9. As in the narrow-body test article, the zoned water spray configurations provided a significant increase in survival time, ranging form 86 to 103 seconds under the conditions tested. Again, the medium flow rate nozzle (0.35 gpm) was more effective than the high flow rate nozzle (0.50 gpm), although by a relatively small amount (10 seconds). Small improvements are also seen from split zoning and elevation of discharge activation temperature in secondary zones (7 seconds).

<u>Commuter Test Article</u>. Currently, small commuter aircraft (19 seats or less) are exempt from the stringent FAA regulations that require seat cushion fire blocking layers and low heat smoke release panels in large transport aircraft. To determine potential improvements in postcrash fire survivability from usage of more fire resistant materials in commuter aircraft, and from a zoned water spray system, a series of full-scale tests were conducted in a Metroliner fuselage.

The fire scenario setup for the commuter test article was similar to that used in the large transport test articles, except on a reduced scale; e.g., 4-by-5-foot pan fire adjacent to 20-by-26-inch initial fuselage opening. The water spray system was comprised of 100 inch long zones, with each zone containing six nozzles. Only 5 gallons of water was discharged.

Figure 10 presents the survival time improvements resulting from fire blocked seats, improved panels and a water spray system. Each fire safety design improvement created finite survival gains. By far the largest increase in survival time was furnished by the water spray system - over 3 minutes. It was also shown in other tests that this incremental improvement would also be attained with less fire resistant materials. It is interesting that the survival time improvement for seat fire blocking layers, 45 seconds, is within the range measured previously in large transport full-scale fire tests (Sarkos, 1989).

6. EVALUATION OF CARGO COMPARTMENT WATER SPRAYS

An in-flight cargo fire presents a totally different fire threat than a postcrash cabin fire. The latter is an intense, open fire which must be suppressed for several minutes in order to enable passengers to escape. A cargo fire, however, may be a deep-seated fire, potentially involving a wide variety of cargo and baggage materials, which must be suppressed and contained within the confines of the cargo compartment. The period of protection must allow the airplane to be safely landed, which in some cases may be as long as 180 minutes.

The cargo compartment water spray tests conducted to date represent a worst case scenario. Since it is expected that water spray will effectively extinguish or suppress a fire originating in bulk-loaded cargo, testing has focused on water spray protection against fires in cargo containers. The test arrangement is shown in figure 11. It would appear that a containerized cargo fire presents greater discharge obstructions and less opportunity for soaking of cargo materials than a bulk-loaded cargo fire (individually loaded luggage and/or cargo). A standard fire load, consisting of cardboard boxes filled with shredded paper at a packing density of 2.5 pounds per cubic foot, was employed in all the tests. An unsuppressed fire burns out of the container through the polycarbonate walls. Aircraft Halon 1301 systems are designed to maintain an inerting concentration of Halon 1301 (>3%) throughout the period of protection, in effect, suppressing a deep-seated fire by preventing the occurrence of open flaming.

Two types of nozzles were evaluated in a zoned water spray configuration - high pressure and dual fluid. The high pressure nozzle produced a water fog at a flow rate of .027 liters/minute; the dual fluid nozzle discharged water mist at 2.5 liters/minute. Since water did not remain suspended in air for any appreciable time with either system, it was necessary to control the discharge of water based on temperature measurements taken within each zone.

The dual fluid nozzle water spray system was evaluated initially. A series of eight tests were conducted, varying the discharge activation temperature (200-300°F), deactivation temperature (150-290°F), and/or spray duration (6-10 seconds). The dual fluid nozzle system was effective in controlling the cargo fire, but the required quantity of water was excessive, ranging from 80 to 110 gallons, and showed little sensitivity to the parameters studied.

The initial tests with a high pressure spray system exhibited some reduction in the required quantity of water (minimum of 65 gallons). However, in order to be a candidate replacement for a Halon 1301 system, the water usage should be in the 10 to 20 gallon range. Therefore, the nozzle arrangement was modified by incorporating nozzles which sprayed directly downward in the space between the containers, in addition to the previous arrangement of nozzles which sprayed horizontally at the ceiling. Figure 12 shows this nozzle arrangement. Also shown is the cargo container fire configuration employed throughout the test program. As shown in Figure 12, the fire origin was in the lower corner container (the adjacent "blank" containers provided discharge obstructions). There were a total of eight spray zones, although only the single zone in which the fire was started activated in all of the tests. The fire zone discharged water at a rate of 1.0 gallon per minute (minimum flow rate required to suppress the fire).

A typical water spray test with the high pressure system is shown in figure 13. A 200°F activation temperature, 20 second spray duration and 10 second scan rate was employed during the test. The ceiling temperature measured above the cargo container was well below the safe level. Also, the oxygen concentration profile demonstrates that the fire was controlled by water spray (versus oxygen starvation). The quantity of water used, 41.3 gallons, demonstrated that the downward spraying nozzles significantly reduced water usage (65 gallons was the minimum quantity when only horizontal spray nozzles were employed). Moreover, in subsequent cargo container fire tests, by modifying certain spray parameters, the fire was controlled for 90 minutes by utilizing only 31.0, 34.4 and 31.6 gallons of water.

In order to evaluate the effectiveness of the spray system during a simulated bulk loaded cargo fire, 56 shredded paper filled boxes were arranged in two tiers of 7 boxes. A second water spray zone with a high concentration of downward spraying nozzles was added because the floor area of the bulk loaded cargo occupied two zones. The flowrate in each of these zones remained at 1.0 gallons per minute (identical to the container test which needed the least amount of water). During the first test, the spray was activated when the ceiling temperature reached 250°F, which allowed temperature excursions within the compartment to reach unacceptable levels (300°F to 800°F). Because the high activation temperature allowed the fire to grow sizably before allowing the system to gain control, an excessive 42 gallons of water was used. The next test used a 150°F activation temperature, which produced noticeably superior results in terms of both the temperatures observed and the amount of water required (24.8 gallons).

7. SUMMARY OF RESULTS

Full-scale tests demonstrated that an on-board cabin water spray system provided significant increases in survival time in all transport aircraft sizes during a postcrash fire. The main benefits of water spray were to delay the onset of flashover, reduce cabin air temperatures, and remove water-soluble toxic gases. Moreover, a zoned water spray system, utilizing relatively small quantities of water, increased the survival time and improved visibility when compared to a system that continuously discharged water throughout the cabin. Enhancement in survivability by zoning was attributed to concentrating the discharge of water to those cabin areas where the fire originated and spread, and to reducing the lowering of the smoke layer caused by water discharge. Full-scale tests also demonstrated that a cargo compartment zoned water spray system, employing either dual fluid or high pressure nozzles, effectively controlled a deep-seated in-flight fire, originating inside a cargo container, for a period of 90 minutes. Significant reduction in water quantities were attained by altering the nozzle arrangement and optimizing certain discharge parameters, such as zone spray activation temperature.

8. THE FUTURE OF AIRCRAFT WATER SPRAY SYSTEMS

The full-scale cabin fire tests described in this paper was part of a broad multi-national program, conducted primarily by FAA and CAA, to determine the feasibility and practicality of an onboard cabin water spray system for enhanced postcrash fire survivability. Various tests and studies were conducted to address the following issues: system effectiveness, system optimization, physiological hazards and other human factors, safety benefit analysis, manufacturer's disbenefits studies, airworthiness requirements and cost analysis (CAA, 1993). It was essentially determined that a zoned cabin water spray system is effective, safe and practical (some protective measures may be needed to tolerate an inadvertent discharge). These findings led to consideration of the of the development and evaluation of a prototype water spray system in an operational aircraft. Further development of a cabin water spray system, however, was discontinued after a cost/benefit analysis determined the high costs associated with life saving potential, approximately $20-30 million per life saved (CAA, 1993).

An aircraft cabin water spray system may still be a viable concept. Although the average benefit based on an analysis of past accidents and factoring in the impact of regulatory fire safety improvements is relatively small, there is the potential for alleviating a major loss of life in a single accident. The potential benefit may be even more pronounced in future, high capacity double-decked transports. Most important, however, is the potential significant reduction in cabin system cost if water spray were also incorporated as a halon alternative fire suppression agent in cargo compartments. It is conceivable that the quantity of water required to suppress a cargo compartment fire will also provide adequate capacity to supply a zoned, cabin water spray system. Utilization of potable water offers added protection and cost reduction depending on the fire scenario, flight type (over land vs. over water), etc.

Initially, aircraft manufacturers and airlines generally favored a gaseous halon replacement agent in cargo compartments, primarily because gases are "clean" and would require virtually no cleanup in the event of an accidental discharge. However, currently available halon replacement gaseous agents have one or more of the following disadvantages: additional weight and volume, greater toxicity, unknown future environmental restrictions, and higher cost. Obviously, toxicity, environmental concerns and cost (agent) are not concerns with water. Freezing is an issue that needs to be addressed. Further reduction in the quantity of water required to suppress a cargo fire may be possible because of the many options offered by zoned water spray. Water spray in aircraft cargo compartment fire

suppression systems is a halon replacement option that exhibits more promise than envisioned several years ago.

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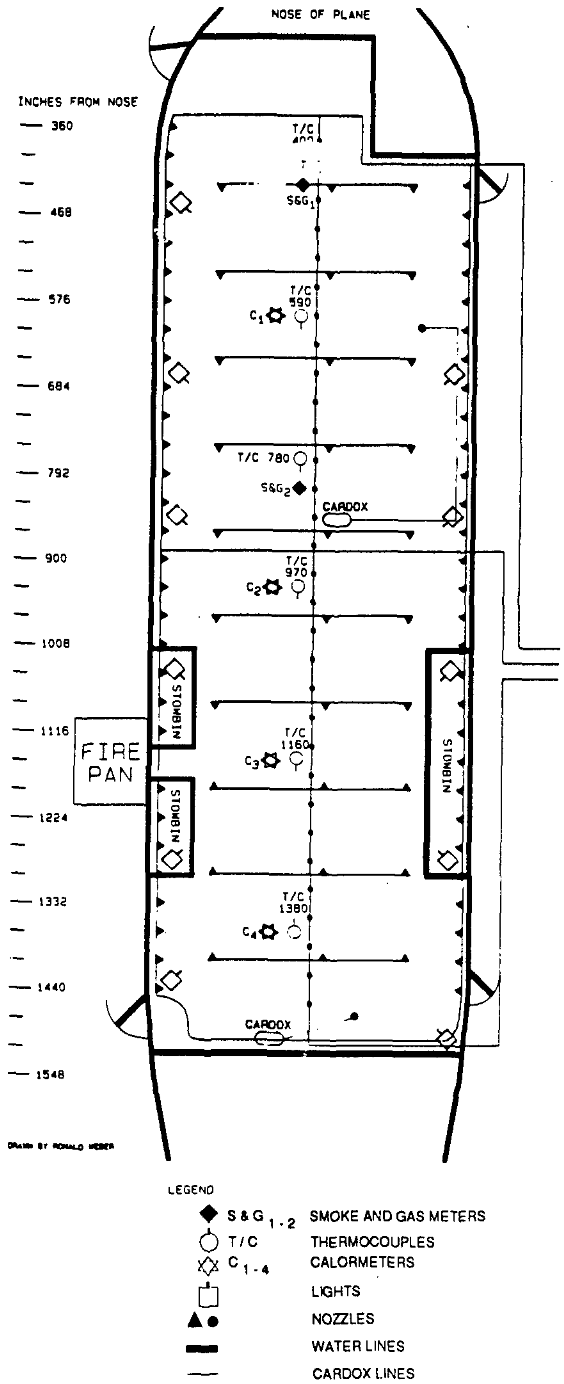


FIGURE 1. NARROW CABIN BODY TEST SETUP, SAVE SYSTEM

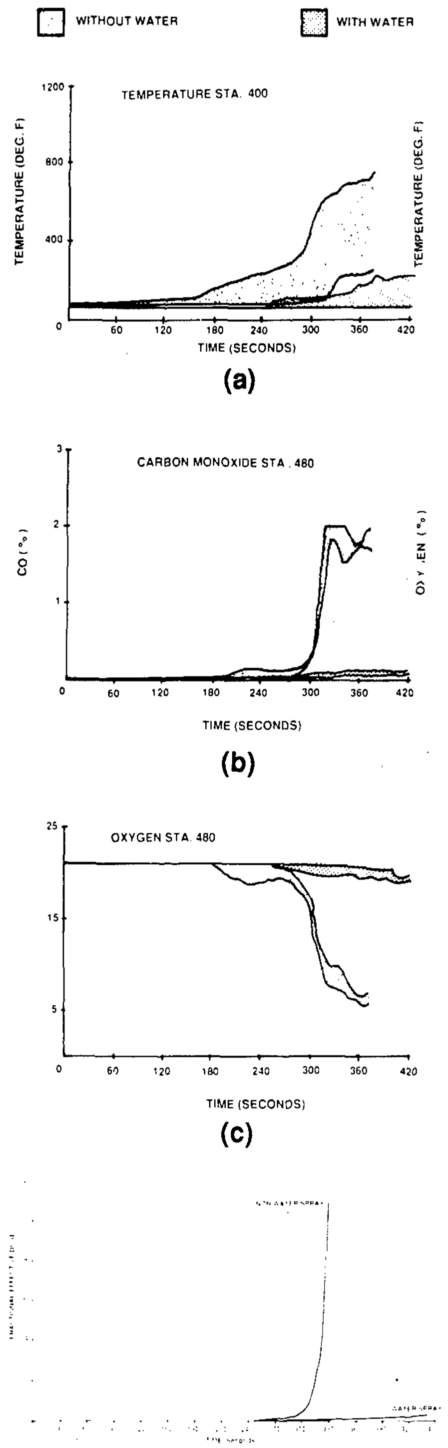


FIGURE 2. NARROW CABIN BODY RESULTS/SAVE SYSTEM/ZERO WIND

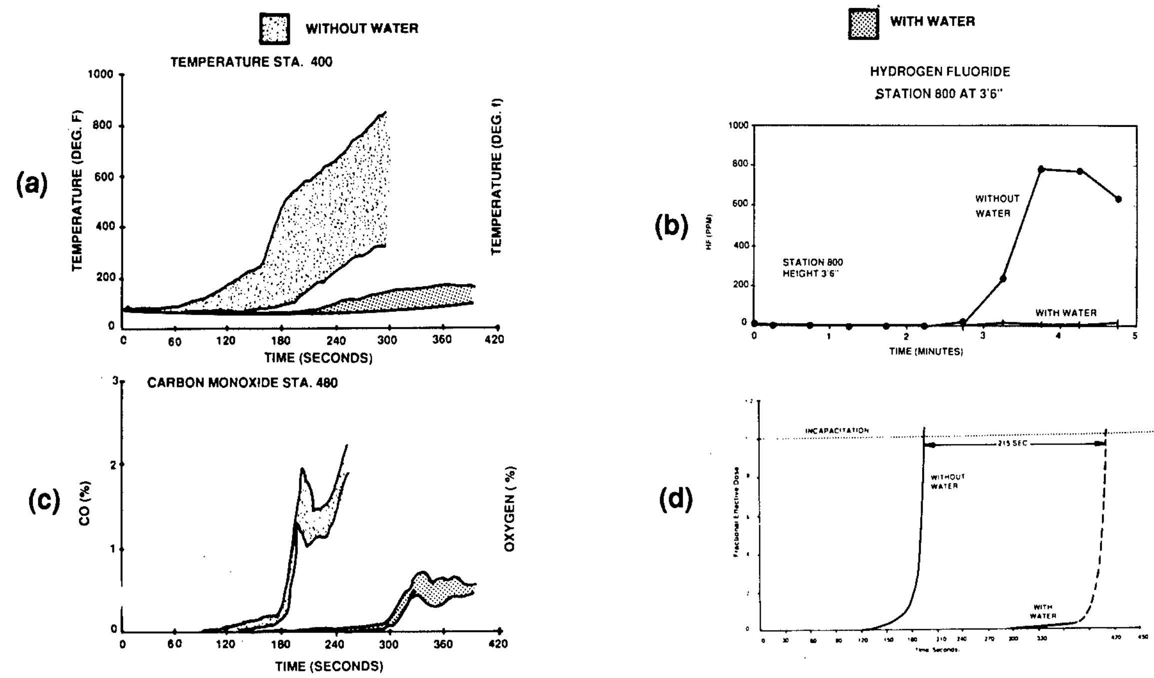


FIGURE 3. NARROW CABIN BODY RESULTS/SAVE SYSTEM/MODERATE WIND

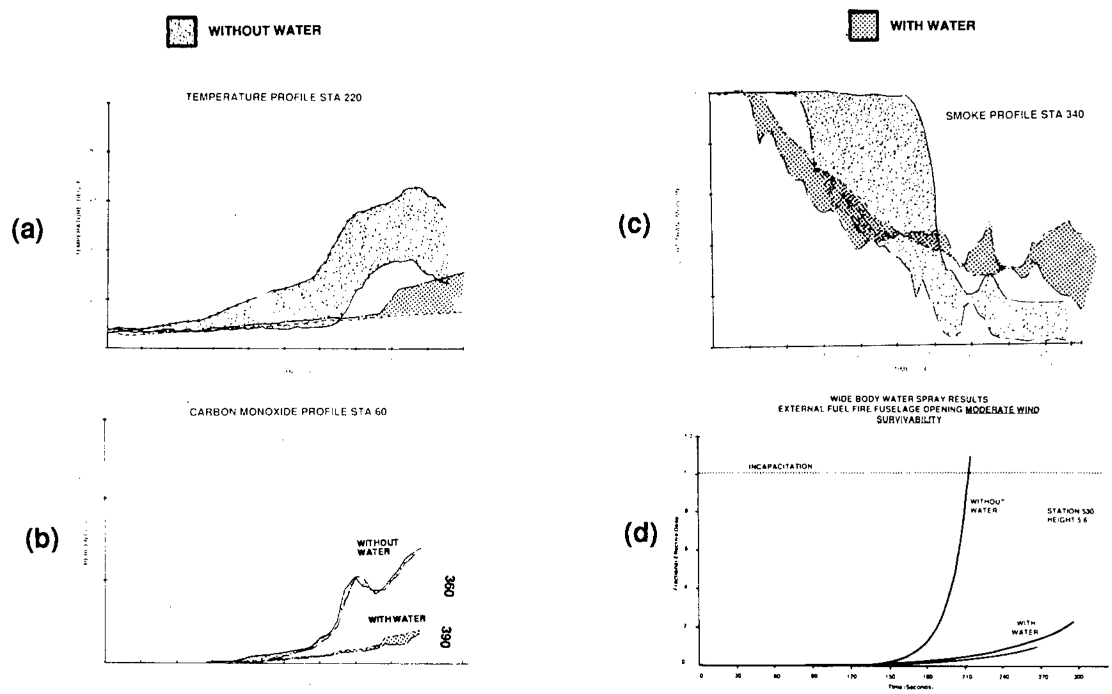


FIGURE 4. WIDE CABIN BODY RESULTS/SAVE SYSTEM/MODERATE WIND

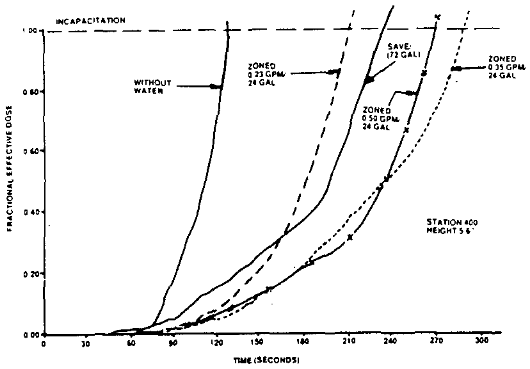


FIGURE 5. CABIN ZONED SYSTEM SURVIVAL TIME IMPROVEMENT, 24 GALLONS

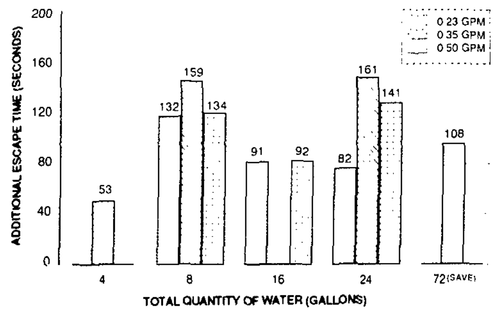


FIGURE 6. CABIN ZONED WATER SPRAY TEST RESULTS ADDITIONAL ESCAPE TIME

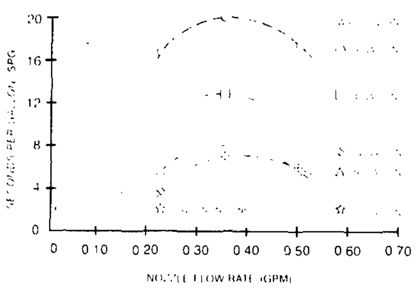


FIGURE 7. CABIN ZONED WATER SPRAY OPTIMIZATION TEST RESULTS

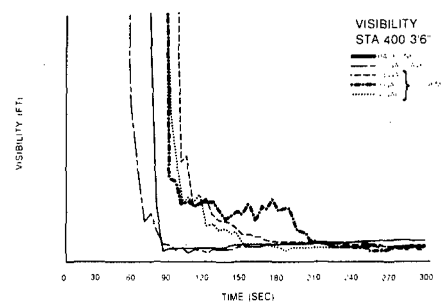


FIGURE 8. CABIN ZONED SYSTEM VISIBILITY IMPROVEMENT

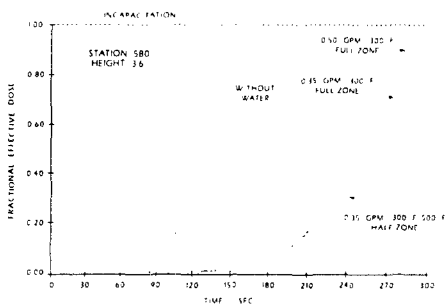


FIGURE 9. WIDE-BODY CABIN ZONED SYSTEM SURVIVAL TIME IMPROVEMENT

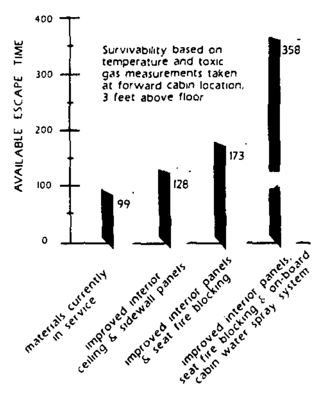


FIGURE 10. SURVIVABILITY IMPROVEMENTS IN COMMUTER TEST ARTICLE

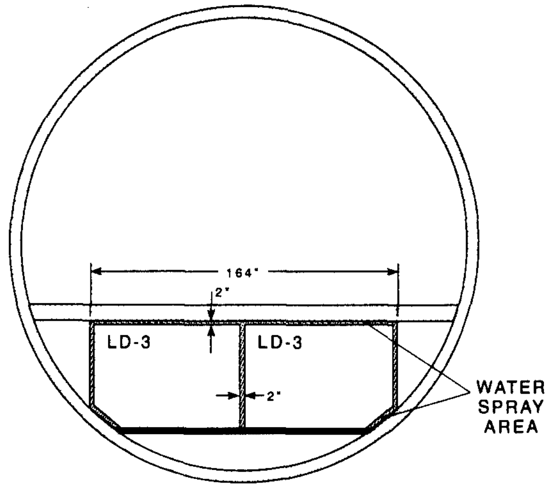
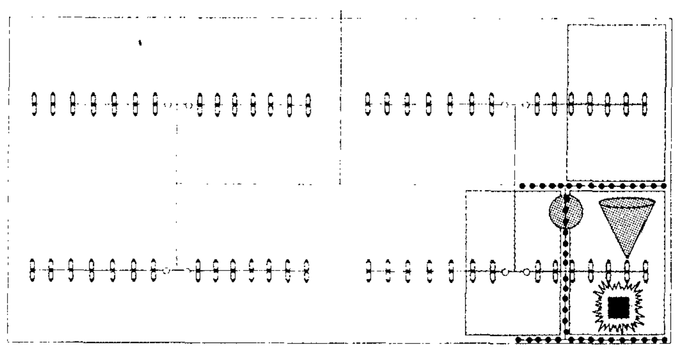


FIGURE 11. DC-10 CARGO COMPARTMENT CROSS SECTION



solenoid valve
nozzle facing downward
nozzle facing horizontally

FIGURE 12. CARGO COMPARTMENT HIGH PRESSURE SPRAY SYSTEM

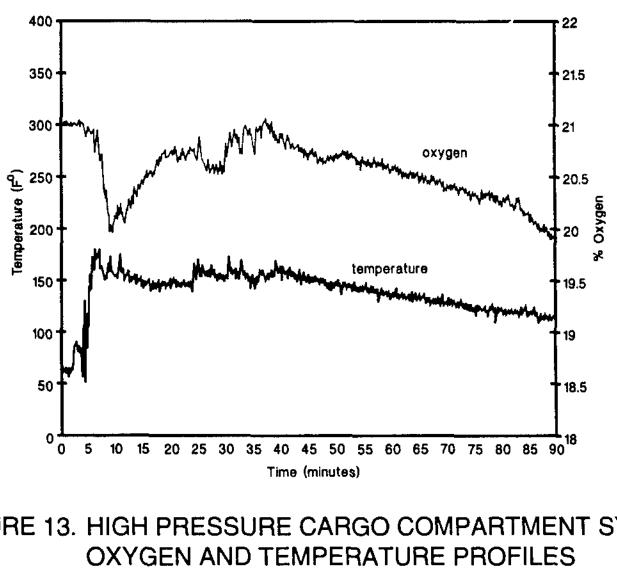


FIGURE 13. HIGH PRESSURE CARGO COMPARTMENT SYSTEM
OXYGEN AND TEMPERATURE PROFILES

DISCUSSION - PAPER NO. 12

A. Mulder (Comment & Questions)

Comment: Very worthwhile research.

Questions:

1) Is there any knowledge about the difference in hazards between inhaling smoke, and smoke mixed with water mist?

2) With respect to Water Spray Systems in cargo compartment, are the so-called 'shaded areas' not a problem?

C.P. Sarkos - Author (Response)

1) What is most important is a comparison of the hazards at a given location and point in time with water spray and without water spray. Measurements during full-scale fire tests with water spray show significantly lower temperatures and toxic gas concentrations than without water spray. Also, the occurrence of flashover is delayed significantly. Similarly, in tests sponsored by the CAA, the collection of particles of various sizes that could be ingested showed lower levels of harmful deposits when water spray was used.

2) FAA cargo compartment fire tests have focused on the 'shaded area' created by a cargo container fire. Until the fire burns out of the container, any water spray discharge will be shielded from the fire. By using a ceiling temperature sensor, the fire could be controlled for 90 minutes by discharging water for 20 seconds if the temperature exceeded 200°F (10-second interrogation time).

N.J. Povey (Comment)

Additional comment to previous questions and answers. The CAA, as part of the joint FAA/CAA/TCCA programme - conducted a study (performed by Dr. David Purser - to investigate the risk posed by respirable water droplets (reported in CAA Paper 93009). Conclusion was that there was no additional risk. The benefit of water in stopping the production of toxic gases far exceeded any additional risk of respirable droplets.

H. Schmidt Question)

Did you investigate the influence of droplet size or droplet size distribution to extinguishing efficiency?

C.P. Sarkos - Author (Response)

We did not investigate the variation of droplet size to determine its effect on extinguishment efficiency. The cabin water spray system employed a mean droplet diameter of about 100μ. One concern for the cabin system was not to employ droplet sizes in the 20-30μ range which might be respirable. Smaller droplet sizes were used in the cargo system with the hope that a total flooding behaviour would result and the droplets would remain suspended for long periods of time.

W.B. de Wolf (Question)

1) Could you comment on the cost/benefit aspect of water spray systems based on the present technical status?

2) Could you also comment on possible patent issues?

R.G. Hill - Author (Response)

1) Cabin water mist systems have not been shown to be cost beneficial at present. However, if a cargo water mist system is shown to be acceptable as a Halon replacement, the cost of additional cabin protection may become cost beneficial.

2) Although some components specific to water mist systems may be patented, the concept is not.

Full-Scale Test Evaluation of Aircraft Fuel Fire Burn-Through Resistance Improvements

Timothy R. Marker and Constantine P. Sarkos
Federal Aviation Administration, William J. Hughes Technical Center

Abstract

Fuselage burn-through refers to the penetration of an external post-crash fuel fire into an aircraft cabin. The time to burn-through is critical because, in a majority of survivable aircraft accidents accompanied by fire, ignition of the cabin materials is caused by burn-through from burning jet fuel external to the aircraft. There are typically three barriers that a fuel fire must penetrate in order to burn-through to the cabin interior: aluminum skin, the thermal acoustical insulation, and the interior sidewall/floor panel combination. The burn-through resistance of the aluminum skin is well known, lasting between 20 to 60 seconds, depending on the thickness. Thermal acoustical insulation, typically comprised of fiberglass batting encased in a polyvinylfluoride (PVF) moisture barrier, can offer an additional one to two minutes if the material is not physically dislodged from the fuselage structure. Honeycomb sandwich panels used in the sidewall and floor areas of transport aircraft offer a substantial barrier to fire; however, full-scale testing has shown that a large fire can penetrate through other openings, such as the seams between sidewall panels, window reveals, and floor air return grilles. Of the three fire barriers, research has shown that large increases in burn-through resistance can be gained by using alternate materials in place of the existing fiberglass based thermal acoustical insulation. In particular, a heat-treated, oxidized polyacrylonitrile fiber was shown to increase the burn-through resistance by several minutes over current insulation, offering potential life savings during a post-crash fire accident in which the fuselage remains intact.

Introduction

Background

In a majority of survivable accidents accompanied by fire, ignition of the interior of the aircraft is caused by burning jet fuel external to the aircraft as a result of fuel tank damage during impact. One important factor to occupant survivability is the integrity of the fuselage during an accident. There are typically two possibilities which exist in an aircraft accident: 1) an intact fuselage, or 2) a crash rupture or an emergency exit opening occurs, allowing direct impingement of external fuel fire flames on the cabin materials. Based on a consideration of past accidents, experimental studies, and fuselage design, it is apparent that the fuselage rupture or opening represents the worst case condition and provides the most significant opportunity for fire to enter the cabin (Sarkos 1988). Past Federal Aviation Administration (FAA) regulatory actions governing interior material flammability were based on full-scale tests employing a fuel fire adjacent to a fuselage opening in an otherwise intact fuselage. This scenario, in which the cabin materials were directly exposed to the intense thermal radiation emitted by the fuel fire, represented a severe, but survivable, fire condition against which to develop improved standards. However, in some crash accidents, the fuselage remained completely intact and fire penetration into the passenger cabin was the result of a burn-through of the fuselage shell (Sarkos 1990). At least 10 transport accidents involving burn-through have occurred in the last 20 years, five in which the rapid fire penetration of the fuselage was a primary focus of the investigation: Los Angeles 1972; Malaga 1982; Calgary 1984; Manchester 1985; and Anchorage 1987.

Accident Data

An example of an accident involving fuselage burn-through with a large loss of life occurred in Manchester, England in 1985. During this accident, a B-737 was approaching takeoff when it experienced an uncontained engine failure, propelling pieces of the engine into the wing, and subsequently rupturing the wing fuel access door area. The takeoff was aborted. As the airplane decelerated, leaking fuel ignited and burned, erupting into a large ground fire after the plane came to rest. Although the fire fighting response was practically immediate, 55 occupants perished from the effects of the fire. In this accident, it was believed that the external fire caused a very rapid burn-through of the lower fuselage skin and quickly involved the cabin furnishings by gaining entry through the baseboard return air grills (reference Air Accidents Investigation Branch 1988 report).

Although fire can penetrate into the passenger compartment by a variety of paths, including the windows, the sidewall (above floor), cheek area (below floor), cabin floor, and baseboard return air grilles, there is no set pattern based on past accidents or experimental test data to indicate which areas are the most vulnerable. Testing had been performed on the individual components (aluminum skin, windows, thermal-acoustical insulation, and interior sidewall panels) but had not been done on the complete fuselage shell system in which fire penetration paths and burn-through times could be observed. For this reason, an initial test program was conducted to determine these mechanisms and the likely time framework required for burn-through to occur.

Experimental

Initial Fuselage Testing

To better understand and quantify the fuselage burn-through problem, the FAA conducted a series of full-scale tests by subjecting surplus aircraft (DC-8 and Convair 880) fuselages to 37 square meter fuel fires (20 x 20 feet). The fuel fires were set adjacent to intact fuselage sections instrumented with thermocouples, heat flux transducers, and cameras to determine penetration locations, fire paths, and important event times (Webster, 1990). Several major findings were concluded in terms of the likely entrance paths of the fire and the time required to involve the cabin interior materials. The tests indicated that the aluminum skin provides protection from a fully developed pool fire for 30 to 60 seconds and that the windows are effective flame barriers until they shrink due to the radiant heat of the fire and fall out of place, allowing flame penetration. These findings were consistent with data obtained during the investigation of the above mentioned accidents. The tests also highlighted the importance of thermal-acoustical insulation in preventing fire penetration. It was observed that the insulation can provide a significant delay in the burn-through process, provided it remains in place and is not physically dislodged from its position by the updrafts of the fire. Several other findings were highlighted, including the ability of the flames to gain access to the cabin by first penetrating into the cheek area and then progressing upward through the floor air return grills. The information obtained during this test project was used as a basis in the development of a full-scale burn-through test rig.

Development of a Full-Scale Burn-Through Test Rig

The next phase of the program involved the development of a test apparatus by which improvements could be evaluated under realistic conditions. The construction of a full-scale test rig was the most practical approach that would allow repetitive testing and systematic evaluation of singular components. To accommodate this, a 6. 1 meter (20 foot long) steel test rig was fabricated, and a 707 fuselage was cut in half, and the test rig was then inserted between the two fuselage halves (Figure 1). This test rig had a 12 x 8 foot section of the outer skin removed which could be mocked-up with aluminum skin, thermal acoustical insulation, floor and sidewall panels, carpet, and cargo liner. The mocked-up test rig extends beyond the 3.0 meter (10 foot long) fire pan, eliminating any edge effects or mating problems that might occur if the test rig/707 fuselage seams were in direct exposure to the fuel fire. Measurements of temperature, smoke, and fire gases (CO, CO_2, and O_2) are taken inside the test rig, along with video coverage at several locations to determine exact burn-through locations and times.

Characterization of the Fuel Fire

Prior to commencement of the mock-up tests, the fuselage exterior surface was instrumented with thermocouples, calorimeters, and radiometers in an effort to quantify test fires at different fuselage locations. During past test programs, ground fires of this size were ignited next to fuselages at the cabin floor level and adjacent to a Type A opening to simulate an open escape exit or fuselage rupture. It was determined from these earlier tests however, that from a burn-through standpoint, a more severe condition results when the fire is beneath the fuselage, allowing the higher temperatures of the upper flame area to come in contact with the lower fuselage. Two fire pan locations were tested, and the location that provided the more severe results of the two was established as the standard fire condition for future material mock-up tests. These tests also provided information on the radiative and convective heat flux produced by fire of this size. Typically, the fuselage skin is subjected to maximum heat fluxes of between 15.9 and 18.2 W/cm^2 (14 and 16 Btu/Ft^2 sec) when measured with a Ther-

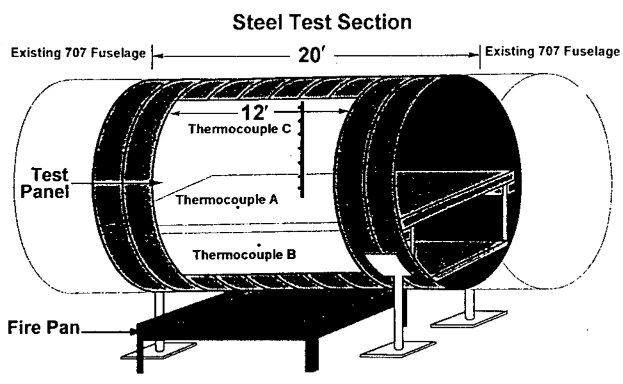


Figure 1. Fuselage burn-through test rig.

moguage calorimeter (combined radiative and convective heat flux). By comparison, a Thermoguage radiometer with a 136 degree angle of incidence (radiative heat flux only) reached approximately 13.6 W/cm^2 (12 Btu/Ft^2 sec).

Initial Baseline Tests

In order to evaluate potential improvements in materials and systems for better resistance to fuel fire penetrations, a baseline test arrangement was established using in-service materials. An aluminum skin section measuring 2.44 m high by 3.66 m wide (8 x 12 feet) was installed where the original skin of the test rig was removed. It consisted of two sheets of 0.16 cm (0.063 inch thick) Alclad 2024 T3 aluminum heli-arced together. The aluminum panel extended from the lower fuselage quadrant up to the window level and was mounted to the test rig stringers and ribs using steel rivets to reduce the potential for separation during testing. The remaining area of the test rig was covered with 22 gauge sheet metal. The first several tests utilized custom made insulation batting, consisting of Owens-Corning Aerocor fiberglass insulation encapsulated in Orcon brand heat shrinkable metallized polyvinylfluoride (PVF) film, type AN-18R. The insulation and batting material was sized to fit in the spaces outlined by the vertical formers and the horizontal stringers of the test rig. The insulation bats spanned the entire area of the aluminum skin, 2.44 x 3.66 m (8 x 12 feet). In the test rig cargo compartment, 0.033 cm (0.013 inch thick) Conolite BMS 8-2A fiberglass liner was installed in both the ceiling and sidewall areas facing the fire and held in place by steel strips of channel screwed into the steel frame of the test rig. An M.C. Gill "Gillfab" 4017 honeycomb floor panel measuring 1.22 x 3.66 m (4 x 12 feet) was installed in the test fig cabin floor area and covered with FAA approved aircraft quality wool/nylon carpet. The remaining test rig cabin floor area consisted of corrugated sheet steel. Interior sidewall panels from an MD-80 aircraft were used; these panels utilized an aluminum substrate which did not meet the current FAA fire test regulations regarding heat release rate. The outboard cabin floor area contained steel plating with 7.62 cm (3 inch diameter) holes to simulate the venting area between the floor and cheek area. Additionally, an aluminum mesh was installed below the sidewall panels to simulate the baseboard air return grills. In general, the major components of a typical aircraft fuselage were represented in the test rig.

During the first test, the fire burned through the aluminum skin within 30 seconds and quickly displaced or penetrated the thermal-acoustical insulation bats, allowing flames to enter the cheek area within 40 seconds. The actual point of first penetration into the cabin was difficult to decipher, since the fire propagated both the sidewall panels and floor return air grills within a short time of one another. Early indications pointed to the lack of complete coverage by the 2.54 cm (1 inch thick) thermal-acoustical insulation, which had been attached to the test rig by loosely packing it into the spaces between the stringers and formers and duct taping all edges. Since a major objective is to determine the effectiveness of the thermal-acoustical insulation when it is not physically displaced, efforts were made to better secure the batting material. The thickness of the insulation was also increased for the next test, as an inspection of several surplus fuselages revealed that the insulation was at least seven centimeters thick in the sidewall area (the insulation actually becomes much thinner at the extreme lower section of the fuselage, due to lesser acoustical requirements). Although the thickness of insulation varies slightly between aircraft, it was found to be at least several plies thick in the corresponding areas of the test fuselage where the fire had penetrated during the first test. The results of the next test were similar to the first in terms of fire propagation paths and burn-through times, but again, it was very difficult to pinpoint the actual path taken because of the visual obstruction due to the placement of the sidewall panels and cargo liner. In order to better understand the burn-through mechanism, the subsequent tests were conducted without sidewall panels, cargo liner, and floor panels to allow greater visualization of the burn-through point and time.

Evaluation of Current Insulation Materials

An evaluation of current fiberglass insulation was conducted in which the effects of the thickness and the method of installation on burn-through time were investigated. A surplus of the Aerocor type insulation material allowed for the conduct of several tests using varying layers. As shown in Figure 2, the first three Aerocor tests utilized 7.62 cm (3 inch thick) Aerocor encased in a heat shrinkable metallized polyvinylfluoride film. The method of Aerocor attachment was refined during each test, as the fire visibly dislodged the batting materials during the first and second tests causing burn-through in 52 and 75 seconds. During the third Aerocor test, heavier spring clips were utilized and installed around the entire perimeter of each insulation bat, which proved to be a very effective attachment system. A fourth Aerocor test was conducted using an additional one inch layer of insulation, which provided an additional 12 seconds. Thus, secured insulation provided about 45 seconds of additional protection after the aluminum skin melted. As a point of clarification, the time to burn-through is determined by visual observation of video cameras located at

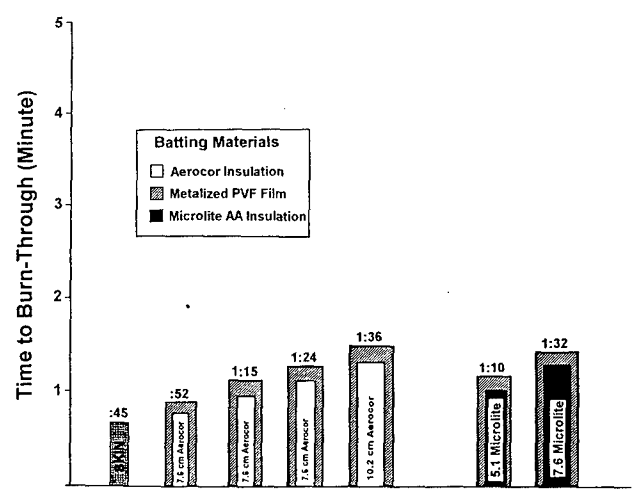


Figure 2. Fuselage burn-through resistance current fiberglass/PVF insulation bags.

various places in the test rig interior. The actual time is somewhat subjective, since the exact time and location are not always clearly defined.

Since the Aerocor is a somewhat dated material, additional tests were conducted using Microlite AA insulation which is currently used on most transport category aircraft. As shown, there was only a marginal increase in the burn-through resistance offered by the three inch Microlite material (1 minute 32 seconds versus 1 minute 24 seconds using a 7.62 cm thickness of Aerocor). The test rig burn-through times compared favorably with past tests using surplus aircraft (Webster, 1994) where flame penetration was observed in approximately 2 minutes 30 seconds. Assuming that the sidewall panels, flooring, and cargo liner in the surplus aircraft likely provided an additional minute of protection, it was concluded that the mock-up tests were a reasonable representation of actual crash fire conditions.

With a realistic and repeatable test condition and the burn-through resistance of current materials defined, improvements in burn-through resistance were evaluated. Considering the thermal acoustical insulation system only, there are two distinct possibilities: 1) modification/enhancement of existing insulation materials and 2) replacement of the current fiberglass insulation with a more fire resistant type.

Evaluation of Modified Current Insulation Materials

The previous burn-through evaluation of existing materials revealed that the metallized polyvinylfluoride film allowed rapid fire propagation from the out-board face of the insulation bat to the in-board face. A candidate replacement film is polyimide (Kapton) which has low flammability/smoke emission characteristics. The use of polyimide or Kapton film as a moisture barrier for commercial aircraft insulation is not new, having been introduced on the L-1011. The Kapton film exhibited improved flame resistance as shown in Figure 3. For

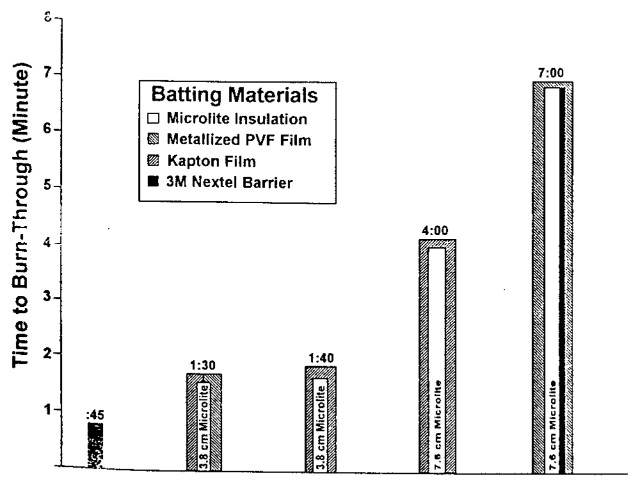


Figure 3. Fuselage burn-through resistance improvements with current fiberglass insulation.

example, comparable burn-through times were exhibited when Kapton was used with half the thickness of insulation (3.81 cm [1.5 inches] as compared to 7.62 cm [3 inches] of insulation with polyvinylfluoride, Figure 2). The most notable test results occurred when 7.62 cm (3 inch thick) Microlite AA was used in conjunction with the Kapton film. This combination was capable of resisting burn-through for four minutes, or an increase of approximately 2 minutes 30 seconds over the identical thickness of insulation material with the polyvinylfluoride film.

A thin fire resistant layer of ceramic fiber material known as Nextel™ was also evaluated. Developed by the 3M Company, Nextel™ ceramic oxide fibers are continuous, polycrystalline metal oxide fibers suitable for producing textiles without the aid of other fiber or metal inserts. The polycrystalline fibers are typically transparent, nonporous, and have a diameter of 10-12 μm. The continuous nature and flexibility of the ceramic oxide fibers allows them to be processed into a variety of textile shapes and forms using conventional weaving and braiding processes and equipment. In this particular arrangement, a nonwoven mat of Nextel™ was being tested full-scale to determine its effectiveness when used as an additional barrier to the existing insulation.

During the test, the Nextel™ was placed inside each of the insulation bats and then encapsulated with the standard polyvinylfluoride moisture barrier film. The Nextel™ was installed

on the out-board face of the insulation bats (within the film) to form a flame propagation barrier between the external flames and the interior of the fuselage. The insulation bats, along with Nextel™ fiber were clamped in place around the perimeter; the clamping also held the Nextel™ in place. This arrangement was very effective, preventing burn-through for nearly seven minutes; although there were visible flames on the backface of the insulation bats, it was difficult to determine what was igniting due to the elevated temperatures (Figure 3). A majority of the Nextel™ was revealed to have remained in place following a post test inspection, however, in several areas it was clear that the Nextel™ had opened, allowing flames to penetrate.

Evaluation of Alternative Insulation Materials

Another series of tests were conducted using an alternate insulation material known as Curlon®, a heat treated, oxidized, polyacrylonitrile fiber (OPF) produced by RK Carbon International, Ltd. Curlon® has a permanent crimp or waviness incorporated into the fiber which aids in the manufacture of lightweight battings used primarily for aircraft insulation. RK Carbon International manufactures the OPF (Panox®) which is then converted in a proprietary heat treating process to form the non-melting, non-burning gray-black Curlon® fiber. Curlon® contains about 70 percent carbon, 20 percent nitrogen, and 10 percent oxygen. It has a diameter of about 8 microns and is considered non-irritating to the skin. Curlon® is also a nonconductor and chemically resistant.

The insulation system incorporating Curlon® is marketed by Orcon Corp. under the tradename Orcobloc™, formerly FB-300, and is unique in that it could potentially be used as a drop-in replacement for the current fiberglass insulation (i.e., it possesses qualities similar to fiberglass for the intended use in aircraft applications). Early versions of the FB-300 were somewhat inferior to the current fiberglass materials in terms of sound absorption and noise attenuation, which is the primary purpose of insulation in the window belt area. The fabrication process was altered slightly to produce a better performing material known as FB-300 SA (superior acoustics). Both materials were tested extensively in the full-scale test rig; the results are shown in Figure 4. The Curlon® material was extremely effective at resisting flame penetration for at least five minutes during several tests. Early concerns over the decomposition products yielded when Curlon® is exposed to elevated temperatures were dispelled, as only trace amounts of hydrogen cyanide were collected during several of the tests.

The performance of the polyvinylfluoride film moisture barriers was also more evident during these tests since the Curlon® material stayed in place for extended periods of time. In doing so, it was clear that the fire was actually propagating along the thin film, around the periphery of the individual bats to the back face. This could present a problem when interior sidewall panels are installed since the burning film may be enough of an ignition source to involve the panels despite the fact that the insulation had not been penetrated. Two additional tests were conducted using Kapton film with the Curlon® for an additional improvement. The backface of the Kapton film did not ignite and was clearly far superior to the polyvinylfluoride film in this respect.

Another alternate material tested was a rigid polyimide foam supplied by the Imi-Tech® Corp. known as Solimide® AC-430. AC-430 has excellent sound absorption, and good thermal insulating properties, but does not compress like fibrous insulation, allowing superior R-values to be achieved. The primary advantage of the foam is its rigidity, enabling the design of an insulation system which spans between aluminum formers (i.e., it does not allow the insulation to directly contact the inside surface of the outer skin) thereby reducing moisture entrapment from condensation. This has been a significant problem with existing insulation systems as they inevitably absorb moisture when in continuous contact with the aluminum skin. Variants of this product are currently in use in the belly area of some newer Boeing commercial aircraft. As shown in Figure 5, three tests were run using rigid polyimide foam as the base material.

During the first test, insulation bats comprised of 7.62 cm (3 inch) of Solimide® rigid foam heat sealed in a bag of Insulfab® reinforced polyimide film supplied by Facile Holdings, Inc.

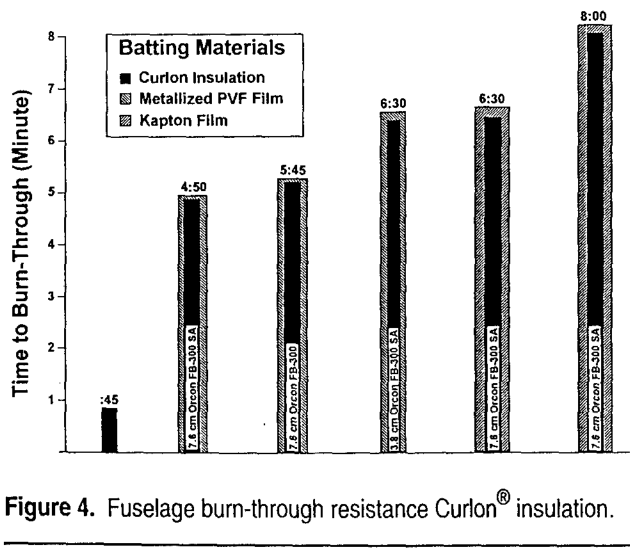


Figure 4. Fuselage burn-through resistance Curlon® insulation.

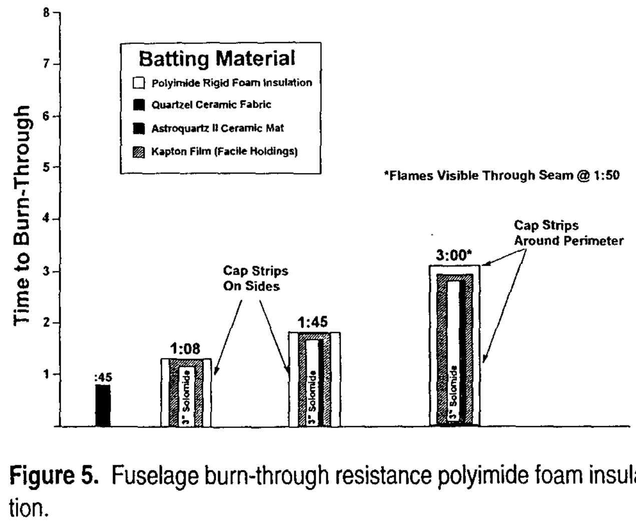


Figure 5. Fuselage burn-through resistance polyimide foam insulation.

Table I. Burn-Through Material Properties

Insulation Batting Materials					
Material Name	**Material Type**	**Density (kg/m3)**	**Density (lb/ft3)**	**Fiber Diameter (μm)**	**Tensile Strength (GPa)**
Aerocor Type PF105WL	Glass Fiber	6.7	0.42	1.5	—
Microlite AA	Glass Fiber	5.5 to 9.6	0.34 to 0.60	1.5	
Curlon®	Heat Treated, Oxidized, Polyacrylonitrile Fiber	3.2 to 6.4	3.2 to 6.4	8	0.65
Solimide®	Right Polyimide Foam	5.3	5.3	n/a	4×10^{-5}
Fire Barriers					
Nextel™	Ceramic Fiber	2,700	168	10 to 12	1.7
Quartzel®	Vitrous Silica Wool	17	1.1	9	—
Astroquartz II®	Quartz Fabric	890	56	9	6.0
Insulation Films					
Material Name	**Material Type**	**Film Thickness (μm)**	**Skrim Material**	**Film + Skrim Weigth (g/m^2)**	**Tensile Strength (GPa)**
AN-18R	Metallized Polyvinyl Flouride Film	50	Nylon	30 ± 5	—
KN-80	Polyimide (Kapton) Film	25	Nylon	46.5	—
Insulfab 121-KP	Polyimide (Kapton) Film	25	Nylon	68.6	—

were installed. The insulation system allowed burn-through to occur at 1 minute 8 seconds, approximately 20 seconds less than fiberglass batting. In an effort to extend the burn-through time, Quartzel®, a vitreous silica wool barrier, was placed in the insulation bats, not unlike the earlier fiberglass enhanced tests with Nextel™. The use of the Quartzel® improved the burn-through resistance of the rigid foam material, but the system was still much less effective than both the Nextel™ enhanced fiberglass system and the Curlon®. The weakness appeared to be at the seam location, which allowed flames to propagate to the in-board face early in the test. After reinspection of the video coverage, it was determined that the system was, in fact, failing at the seam, rather than because of burn-through of the material. In an effort to rectify the problem, horizontal "cap strips" were used in addition to the vertical cap strips already used in the previous tests to hold the insulation to the test frame. A third test was conducted with this arrangement and the use of another fire blocking material known as Astroquartz II®, a quartz fabric. The additional horizontal cap strips aided in extending the burn-through time, but, it was still not close to the level attained by the other systems. A future test has been planned to repeat the third test using an installation that would allow direct attachment of the fire blocking material to the test frame, similar to the attachment method used during the Nextel™ enhanced test. Known properties of the materials used in the full scale tests are included in Table I.

Development of a Medium Scale Test Rig

Much of the research on fuselage burn-through was a joint effort between the FAA and the United Kingdom Civil Aviation Authority (CAA). In particular, the FAA was responsible for the development of the full-scale test apparatus described above, while the CAA had tasked Darchem Engineering to develop a medium-scale test apparatus. During the early phase of this joint research program, it was determined that the development of a small or medium scale burn-through test facility could be beneficial in investigating the problem of burn-through. A laboratory test facility which could replicate the full-scale conditions allows for quick and inexpensive testing of improved materials and/or systems and also serves as a screening device for evaluating new materials under consideration. To date, Darchem has developed the testing apparatus and has logged hundreds of hours of testing at the Faverdale Technology Centre (FTC) in Darlington. The medium scale facility has proven to be an effective screening tool for materials under consideration and enables new protection systems to be developed. It is anticipated that the apparatus will compliment research conducted in the FAA full-scale test rig in order to bring about improvements in the burn-through resistance of fuselages.

Conclusions

Summary of Results

From the results of the initial full-scale surplus aircraft tests, as well as the several series of tests completed in the burn-through test rig, it is evident that the aluminum skin provides 30 to 60 seconds of protection prior to melting and, subsequently, allowing flame impingement on the thermal-acoustical insulation. The aluminum skin currently in use offers little opportunity for fire hardening and will likely be used in next generation aircraft to a large extent. This leaves the focus of extending the burn-through resistance on the thermal-acoustical insulation and the floor/sidewall panel combination and related components. Full-scale fire tests have shown that appreciable gains in burn-through resistance can be achieved by either protecting or replacing the current fiberglass thermal acoustical insulation. As shown in Figure 6, using a Kapton film bagging material in place of the current polyvinylfluoride film alone may provide an additional three minutes of protection. Also, a lightweight ceramic matt placed on the out-board face of the fiberglass insulation prevented burn-through over a nearly seven minute test duration. The most effective replacement combination was a heat stabilized, oxidized polyacrilonitrile fibrous material (Curlon®) encased in a polyimide film. This combination resisted burn-through for eight minutes. The Curlon® did not ignite or burn when subjected to the fuel fire. The Kapton film prevented any flame spread on the in-board face. Moreover, the Curlon® has the ability to be used as a direct drop-in replacement for the currently used material.

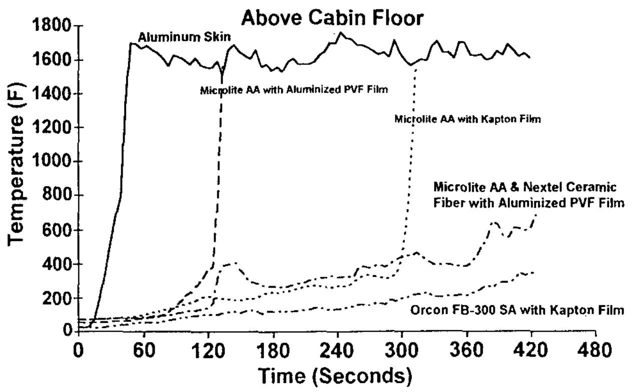


Figure 6.

Future Considerations

Air Return Grilles

Once a fire penetrates the thermal acoustical insulation, it can quickly gain access to the cabin via the air return grill system. The use of intumescent coatings may be a simple concept for delaying grill penetration (and could be used for the enhancement of the backface of interior panels to prolong their burn-through capabilities).

Aluminum Versus Steel Structure

Although the enhanced and alternate insulation materials tested produced results which were very promising, it should be noted that the tests may be biased due to differences between the test rig and an actual aircraft fuselage. The most significant is the use of a steel structure in the test rig, which will not collapse during a test. For this reason, tests will be conducted with actual aircraft structure to investigate the effect of the aluminum structure on burn-through resistance improvement.

Attachment Methods

In conjunction with the tests using aluminum aircraft structure, a thorough investigation of the attachment methods will be conducted. The method of attachment is critical if burn-through resistance improvements are to be realized. It may be possible to obtain several minutes additional protection from burn-through using current materials by simply using attachment clips that won't melt and fail during exposure to external fires. Currently, there are several different methods of insulation bat attachment, most of which consist of thermoplastic washer type fasteners. In addition, many of the current insulation bats are attached directly to the backface of the fuselage skin via fasteners mounted using pressure sensitive adhesives which will quickly fail when heated from fuel fire exposure.

Windows

The cabin windows must also be protected against burn-through by an external fuel fire. The pressure pane located on the outermost surface is constructed of stretched acrylic which shrinks when exposed to heat and flames. Once this occurs, the pressure pane falls out of place, allowing the flames to impinge on the fail-safe pane which will similarly fail in short duration.

Airframe manufacturers would be reluctant to modify the pressure pane; however, it is possible that the fail safe pane could be enhanced to contribute to the improved fire resistance of the aircraft fuselage.

Totally Composite Fuselage

Another area that will be studied is the burn-through resistance of a composite skin fuselage. The use of composites in transport category aircraft has grown steadily due to their high strength and low weight. The fuselage skin of the High Speed Civil Transport (HSCT) will likely be constructed of a composite material which requires an assessment of its performance when exposed to a large fuel fire. From a burn-through standpoint, a composite fuselage would likely offer greater burn-through protection than aluminum. However, there is concern over the potential for toxic and combustible gases being released during flame exposure, which could present a hazard to escaping occupants. Whether or not this is a real concern will be determined in the full-scale test rig by replacing the aluminum skin with composite structure and measuring the resultant gases within the cabin.

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AIRCRAFT FIRE SAFETY

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DEVELOPMENT OF IMPROVED FIRE SAFETY STANDARDS ADOPTED BY THE FEDERAL AVIATION ADMINISTRATION

Constantine P. Sarkos
Manager, Fire Safety Branch
Federal Aviation Administration Technical Center
Atlantic City International Airport, NJ 08405
U.S.A.

SUMMARY

This paper summarizes a series of improved fire safety standards for transport aircraft adopted or proposed by the United States Federal Aviation Administration over the past five years and describes the technical development of these standards. Important test results and analyses employed to develop the new standards are described. Reference is made to technical publications issued by the FAA for each fire safety area. Emphasis is placed on recent and high-impact rulemaking actions such as the heat release standard for large surface area interior panels (based on the Ohio State Rate-of-Heat-Release Apparatus). Other activities summarized include heat resistance evacuation slides, smoke detectors and fire extinguishers, cargo compartment fire protection, seat cushion fire blocking layers, floor proximity lighting, and crewmember protective breathing equipment.

INTRODUCTION

The Federal Aviation Administration (FAA) has undertaken an unprecedented series of regulatory actions over the past five years for the purpose of improving transport aircraft interior fire safety. These initiatives were part of a broad, scheduled program to enhance airliner safety that includes such diverse topics as water survival, child restraints, and crashworthiness (1). They are a culmination of a number of factors, including advisory committee recommendations (2), congressional support, product oriented FAA technical programs, accident pressures, and industry cooperation.

Aircraft interior design for fire safety covers three broad areas: material fire test methods, fire management and suppression, and evacuation and survival. Because of the overriding concern with the effect of the hazards of burning interior materials on occupant survivability, the FAA has placed greatest emphasis in its research, engineering and development program for cabin fire safety on the development of improved fire test methods for interior materials. Products from this program were incorporated into new fire test standards for seat cushion fire blocking layers (3), low heat/smoke release interior panels (4,5), burnthrough resistant cargo liners (6), and radiant heat resistant evacuation slides (7). New requirements for detectors and extinguishers (8) will improve in-flight fire management and suppression. Evacuation and survival has been enhanced by new standards for floor proximity lighting (9) and flight crewmember fixed protective breathing equipment and cabin crewmember portable protective breathing equipment (10).

SEAT CUSHION FIRE BLOCKING LAYERS

Aircraft seats are typically constructed of fire retardant polyurethane foam and upholstery fabric, which previously was required to pass the vertical Bunsen burner test prescribed in Federal Aviation Regulation (FAR) 25.853 (11). However, under the conditions of a severe cabin fire, the foam core ignites readily and burns rapidly, significantly contributing to the spread of fire. The concept of a fire blocking layer material to encapsulate and to protect the polyurethane foam was recommended for evaluation and development by the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee (2).

The initial phase of FAA evaluation consisted of a series of full-scale tests to determine the effectiveness of the seat cushion fire blocking layer concept under the conditions of an intense postcrash fuel fire. Prior work by others was limited to the evaluation of fire blocking layers under moderate fire conditions for office, theater, institutional, and surface transit vehicle settings. The FAA full-scale tests were conducted in a new building with the capability of subjecting aircraft test articles to large jet fuel pool fires under controlled environmental conditions (12). A C-133 airplane modified to resemble a wide body interior was employed as the test article (figure 1). Basically, a section of the C-133 test article was lined and furnished with actual cabin materials and subjected to an intense external fuel fire placed adjacent to a simulated fuselage rupture. The results of four tests with modified seat cushions (13), but with all other test aspects identical, are shown in figure 2. In this figure the fractional effective dose (FED) accounts for the assumed additive effect of measured levels of toxic gases and elevated temperature on survival (12). An FED value of unity corresponds to incapacitation and indicates the hypothetical survival time. The additional time available for escape when the seats were protected with Vonar™ and Norfab™ fire blocking layers was 60 and 43 seconds, respectively, and was comparable in the case of Vonar to the safety benefits provided by noncombustible foam cushions. Further testing demonstrated that blocking layers could provide even greater improvements against certain types of ramp and in-flight fires, for example, preventing fires that may otherwise become out of control when initiated at an unprotected seat and left unattended (14). Although these data demonstrate the efficacy of the fire blocking layer concept, extensive additional FAA work was needed to make the concept into a viable product. This additional work covered the subjects of weight optimization and durability (15), flotation (16), cost-effectiveness (17), and certification testing of cushions (18).

The final rule established that transport aircraft seat cushions meet new and more severe flammability requirements by November 26, 1987 (3). The new test methodology, developed by FAA, subjects seat back and seat bottom cushion specimens to a burner with temperature and heat flux typical of a cabin fire (figure 3). Unlike most flammability tests, the test specimens simulate the end use seat configuration and allow for the burning interaction of upholstery cover, fire blocking layer, and foam cushion. In addition, other important effects such as seat construction features (thickness, seams, foam layering, etc.) and the melting, dripping, and pool burning behavior of urethane foam are taken into consideration. Acceptance criteria consist of 10 percent weight loss and a burn length of 17 inches - performance essentially matching that attained by the Vonar™ and Norfab™ blocking layer materials proven effective in full-scale tests. An advisory circular was issued by FAA to provide guidance material for testing seat cushions to show compliance with the rule (19).

Approximately 350 fire blocking layer materials were evaluated by FAA following the development of the seat cushion flammability test methodology. About 130 materials met the performance criteria, including, for example, thin foams, fiberglass cloths, aluminized fabrics, and graphitized fabrics, demonstrating the availability of suitable fire blockers. Many of the materials later proved to be impractical from weight, comfort, and durability considerations upon subsequent indepth evaluation by seat manufacturers. Today, the majority of seats manufactured in the United States are constructed of either polybenzimidazole felts or aramid fire resistant quilts, weighing 6 to 10 ounces per square yard. The entire United States airline fleet, consisting of approximately 650,000 seats, is protected with seat cushion fire blocking layers.

LOW HEAT RELEASE INTERIOR PANELS

The interior panels of an aircraft cabin, such as the sidewalls, ceiling, stowage bins, and partitions, are very important to the cabin fire load because of their large surface area and, in some cases, location in the upper cabin where fire temperatures are greatest. This importance was evidenced in the full-scale fire tests with fire blocking layers (figure 2). In the test with noncombustible seat cushions, the flashover was caused primarily by the burning panels. Interior panels are usually complex composites consisting generally of a Nomex™ honeycomb core, resin-impregnated fiberglass facings, and a decorative laminate finish.

The next logical step in fire-hardening the interior of a transport aircraft, after the establishment of a seat cushion flammability standard (3), was to improve the fire performance of the interior panels by development of more stringent and new fire test requirements. The issue of improved test methodology was complicated by the requirement to consider the interrelated concerns of flammability, smoke, and toxicity. However, test methodology development was preceded by the need to document (by full-scale fire tests) the potential benefits of fire-hardened panels for several fire scenarios.

The potential for improved safety was examined in the C-133 wide body test article used earlier for evaluation of the effectiveness of seat cushion fire blocking layers. A section of the test article was fitted with sidewalls, stowage bins, a ceiling, and a partition, each constructed of an advanced composite panel selected by the National Aeronautics and Space Administration (NASA), as well as fire blocked seats and carpet, and subjected to three types of full-scale fire conditions. The same tests were repeated with a panel design used extensively in early wide body interiors and still retained for some interior applications. The safety improvement associated with the advanced panel when compared to the in-service panel was significant. With the advanced panel, flashover was actually prevented when the external fuel fire was adjacent to a door opening or when an in-flight fire was started from a gasoline drenched seat. In the more severe ruptured fuselage scenario, wherein seats are more directly exposed to the external fuel fire, use of advanced panels resulted in a 2-minute delay to the onset of flashover (20).

The full-scale fire tests in the C-133 wide body test article, conducted to examine the benefits of seat cushion fire blocking layers and fire-hardened interior panels, demonstrated that occupant survivability was largely driven by cabin flashover. Flashover may be defined as the sudden and rapid uncontrolled growth of fire from a relatively small area surrounding the ignition source to the remainder of the cabin. Typical C-133 test data exhibiting this behavior are shown in figure 4. Before the onset of flashover, which occurred at about 150 seconds, the smoke and toxic gas levels were minimal and survival was clearly possible. After the onset of flashover, smoke and toxic gas levels and temperature increased rapidly to a level that would have made survival highly unlikely.

It should be noted that flashover is a phenomenon that generally occurs when fire in an enclosure generates heat at some critical rate that is effected by heat transfer and ventilation. Flashover to a large degree is caused by the heat release rate of burning interior materials. Thus, a rate of heat release test methodology will tend to yield the contribution of a given material to the flashover event. Also, selection of interior materials on the basis of minimizing heat release rate also serves to implicitly reduce the cabin smoke and toxic gases hazards since it is the flashover event that generates hazardous quantities of combustion products (figure 4).

Several studies were conducted to correlate the performance of composite panels in a heat release test device and under realistic cabin fire conditions. Initially, a variety of laboratory flammability tests were evaluated in terms of panel performance with results in a 1/4-scale cabin model (21). The Ohio State University (OSU) rate-of-heat-release apparatus exhibited the best correlation with model fire test results. Although probably any of the available heat release rate tests would serve to yield the flashover potential of various panel materials, the OSU apparatus was selected specifically for further evaluation and development. The decision to select the OSU

apparatus was based on the above correlation study as well as recommendations of the SAFER committee (2), the use of the OSU apparatus in the development of the Combined Hazard Index (22), the availability of the OSU apparatus with the airframe manufacturers and its standardization by the American Society of Testing and Materials (ASTM). A second study corroborated the earlier good correlation results in that it established an inverse relationship between heat release measurements in the OSU apparatus and the time-to-flashover of a series of composite panels evaluated in the full-scale C-133 test article under postcrash fire conditions (23).

The second correlation study involved C-133 tests of five composite panel constructions under a scenario consisting of an external fuel fire adjacent to an open door. To realistically evaluate panel performance, the flat panel test specimens were installed in a typical configuration that included sidewalls, stowage bins, a ceiling and partitions (figure 5). In this arrangement, other factors such as ease of ignition and flame spread rate for the panels, as well as the contribution of fire-blocked seats and carpet, were allowed to come into play. The results of these tests are shown in figure 6 as an FED history plot. The graph indicates a wide range in behavior for the five types of panels. The phenolic/Kevlar™ and epoxy/fiberglass panels displayed the earliest flashovers, whereas the phenolic/fiberglass panel delayed flashover by about 3 minutes. Moreover, there was a monotonic, inverse relationship between heat release measured by the OSU apparatus and time to flashover. Also, the data indicate that small changes in heat release by materials may result in large changes in the time to cabin flashover.

The actual criteria for material selection were driven by the level of benefits evidenced by full-scale testing. The phenolic/fiberglass panel tested well under virtually any test condition (23), and this construction was achievable by state-of-the-art manufacturing processes. Thus, the phenolic/fiberglass panel was used as a benchmark for selection of the performance criteria for OSU testing of panel materials. A pass/fail criterion of 65 kw-min/m^2 for a 2-minute total heat release was selected to embrace the performance of the phenolic/fiberglass panel. An additional criterion of 65 kw/m^2 for peak heat release rate was included to eliminate usage of those materials that burn rapidly but produce small quantities of heat because of their low weight. The final rule also contains a new requirement for smoke emission testing in order to minimize the possibility that emergency egress will be hampered by smoke obscuration (5).

A schematic of the OSU apparatus is shown in figure 7. The equipment is basically a flowthrough device that measures the heat release rate as a function of time by a material subjected to a preset level of irradiated heat. Although the relationship between heat release rate data measured by the OSU apparatus and cabin fire conditions was demonstrated, the OSU data have been found to be sensitive to certain design features and operational conditions. Three round-robin test programs between FAA and the United States Aerospace Industries Association (AIA) were necessary to reduce the reproducibility of data between laboratories to an acceptable level (24). Results from the third round robin, with Boeing, Douglas, OSU, and FAA as participants, however, indicate that consistent results are attainable (figure 8). For example, the reproducibility of the third round robin, as measured by the percentage average relative standard deviation, was 7.7 and 7.8 percent for total heat release and peak heat release rate, respectively (24). Moreover, in a more recent round robin involving FAA and four laboratories in Europe, the reproducibility was quite acceptable after the initial comparison - 5.4 and 10.9 percent for total and peak measurements, respectively.

CARGO LINER BURNTHROUGH RESISTANCE

Lower cargo compartments in large transport aircraft are categorized as either class C or class D types (11). The latter are small compartments designed for fire containment by oxygen starvation, while the former are larger compartments that are required to have a fire detection and suppression system. FAA conducted full-scale fire tests to investigate the resistance of cargo liners to flame penetration for both compartment classifications. In a class D compartment, where it is critical that liners not be breached in order to allow oxygen starvation to take place, it was found that some types of liners failed (25). Fiberglass liners resisted burnthrough, whereas Nomex liners were penetrated by the flames (figure 9). It was concluded that a class D cargo fire was controllable if fiberglass or equivalent were the liner materials; but, if Nomex were used, the fire would continue to burn because of the availability of oxygen due to liner failure. In tests conducted inside a class C cargo compartment, even with a detection/suppression system, liner burnthrough resistance equivalent to fiberglass was required to ensure fire suppression under all scenarios (26). For example, Kevlar liner burnthrough occurred when sudden, intense flaming fires were employed and when a time lapse was allowed between the points of detection and discharge of suppression agent. Although the fire may be suppressed by the agent, it was determined that the breached cargo liner would cause a more rapid depletion of agent concentration and re-ignition at an earlier point in time than in an intact compartment. The main conclusion from the testing was that a more realistic and severe test requirement was needed for cargo liners used in both class C and class D cargo compartments.

A new fire test method that measures the burnthrough resistance of cargo liners, shown in figure 10, was developed with the features of severe liner exposure (matching the maximum heat flux and temperature measured during full-scale tests) and realistic ceiling and sidewall liner orientation (27). This test method is the basis for more stringent test requirements in newly certified aircraft (6) and a similar proposal for certain transports now in service (28). Criteria for acceptance are that there must be no flame penetration of ceiling and sidewall specimens and that the temperature measured above the ceiling specimen must not exceed 400 °F. The flame penetration criterion can be met by fiberglass liners but not by Nomex or Kevlar liners (27). However, many fiberglass liners cannot meet the peak temperature criterion because of the type or weight of resin and type of cloth weave (29). It appears that fiberglass suitably tailored to meet the peak temperature criterion will be the material of choice for new burnthrough resistance requirements although several new materials or combinations are being studied.

In a more recent, separate action, the FAA has proposed a new airworthiness directive (AD) for "combi" airplanes certified with a main deck class B cargo compartment (30). This action was prompted by the loss of a 747 airplane that apparently developed a major fire in the main deck cargo compartment. The AD proposes design changes that would require that the class B compartments be modified to a class C configuration or that burnthrough resistant cargo containers, meeting the more stringent test requirements for cargo liners (6) and employing smoke detection and extinguishing systems, be used to carry all cargo.

RADIANT HEAT RESISTANT EVACUATION SLIDES

In 1978, a DC-10 experienced an aborted takeoff resulting in a major jet fuel fire and the resultant collapse of a deployed evacuation slide caused by radiant heat damage. Although the two fatalities were not attributable to loss of the slide for emergency egress, the FAA undertook a test and development program to improve the radiant heat resistance of slide fabrics. From a series of full-scale fire tests in which pressurized slides were subjected, at various distances, to a 30-foot-square fuel fire, it was determined how slides failed and the time duration for failure (loss of pressurization) to occur (31). For example, a typical urethane nylon slide, located 15 feet from the edge of the fuel fire, where the irradiance was 1.5 Btu/ft^2-sec, failed in 25-30 seconds on the plain surface (non-seam area). Also, it was shown that an aluminized reflective coating significantly improved the airholding qualities. The uncoated urethane nylon slide that failed in 25-30 seconds held pressure for 70-75 seconds when protected with an aluminized coating and loss in pressure occurred at an opened seam.

To permit the development and qualification of improved slide fabrics, a laboratory test was developed (31). The essential features of the laboratory test, shown in figure 11, are a radiant heater, calorimeter, pressure holding cylinder, specimen holder, pressure gage, pressure transducer, and recording device. Basically, a slide fabric specimen is mounted to the pressure holding cylinder which is then pressurized. The irradiance to the specimen is set by the calorimeter. Pressure holding capability of the specimen at the set irradiance level is determined by the recorded pressure history.

On June 3, 1983, FAA issued Technical Standard Order (TSO)-C69a, Emergency Evacuation Slides, Ramps, and Slide/Raft Combinations, which made general improvements to the equipment requirements and contained new requirements for radiant heat resistance (7). TSO-C69a required that all evacuation slides purchased after December 3, 1984, meet the new standards. For radiant heat resistance, the requirement is retention of pressure for 90 seconds at an irradiance of 1.5 Btu/ft^2-sec. The pressure holding members of all TSO-approved inflatable evacuation slides are now constructed of aluminized materials in order to provide adequate radiant heat resistance.

SMOKE DETECTORS AND FIRE EXTINGUISHERS

As the result of investigations of in-flight fires, including the Air Canada DC-9 on June 2, 1983, (that resulted in 23 fatalities) and an inspection survey of the United States air carrier fleet, the FAA amended the FARs with the following requirements: a smoke detector in each lavatory, an automatic fire extinguisher in each lavatory trash receptacle, increased number of hand fire extinguishers, and the use of Halon 1211, or equivalent, as the extinguishing agent in at least two of the hand fire extinguishers (8). A separate time period was specified for implementation of each requirement, with the longest period extending to April 29, 1986.

FAA supportive experimental and analytical studies for these amended regulations have concentrated on the effectiveness and safety of Halon 1211 (bromochlorodifluoromethane) hand extinguishers. Initial tests showed the superiority of Halon 1211 in knockdown and extinguishment capability against fuel drenched seat fires in comparison to water, dry chemical, and carbon dioxide extinguishers. However, opposition to the usage of Halon 1211 centered on the toxicity associated with the agent and, in particular, its decomposition products. Subsequent tests by the FAA clearly showed that virgin agent and decomposition gas concentrations peaked at levels significantly below values considered dangerous and rapidly dissipated due to the effect of adsorption, stratification, dilution, and ventilation (32). Typical gas profiles measured near an extinguished seat fire in the C-133 test article are shown in figure 12. Hydrogen fluoride (HF) and hydrogen bromide (HBr) concentrations peaked at about 10 parts per million (ppm), hydrogen chloride (HCl) peaked at 17 ppm, and the peak virgin agent concentration was 1800 ppm (0.18 percent). Most importantly, it became evident that the hazards associated with an uncontrolled seat fire would quickly surpass those transient hazards resulting from Halon 1211 decomposition (32) and would possibly result in cabin flashover within 3 to 4 minutes if left unchecked (13).

To place a conservative upper limit on the quantity of agent that could safely be discharged inside a compartment, a perfect stirrer model was used to analyze the decay of agent concentration due to ventilation (33). Nomographs developed from this analysis predict maximum safe agent weight for a given compartment volume and ventilation rate and are incorporated in a revised advisory circular (AC) on hand fire extinguishers (34).

In related studies, the FAA has examined the safety of Halon extinguishing agent discharge in small airplanes (35,36,37). A major concern is the warning label on Halon bottles against discharge in a small enclosure volume. For example, for the common size 2 1/2 pound Halon 1211 extinguisher, the upper volume limit for "safe" agent discharge is 312 cubic feet. However, FAA tests conducted under simulated flight conditions in a Cessna 210 with a cabin volume of 140 cubic feet clearly

demonstrated that both Halon 1211 and Halon 1301 could be safely discharged in this relatively small airplane cabin (35,36). The absence of significant concentrations of agent near a seated occupant was shown to be primarily the result of accumulation of the heavy agent near the floor and, to a lesser degree, high cabin ventilation rates. Apparently, the Halon bottle warning labels are based on safety factors for human exposure as well as assumptions of zero ventilation and homogeneous agent distribution. Fire tests conducted inside a Piper Commanche airplane also demonstrated the effectiveness of Halon 1211 and Halon 1301 in extinguishing hidden electrical and hydraulic fires behind an instrument panel (37). In summary, the safety and effectiveness of Halon hand-held extinguishers has been demonstrated for both large and small airplane cabin applications.

FLOOR PROXIMITY LIGHTING

Rapid passenger evacuation is the most critical and overriding consideration in postcrash cabin fire safety. Buoyant hot smoke from a cabin fire, however, clings to the ceiling and rapidly obscures conventional ceiling mounted emergency illumination and exit signs, thereby reducing the visibility of occupants and prolonging evacuation time. The resultant reduction in visibility and escape guidance often occurs when the lower portion of the cabin is relatively free of combustion products. FAA tests have demonstrated the effectiveness of emergency lighting placed below the smoke layer in the proximity of the cabin floor. In one study, the improved visibility of floor proximity lighting systems, including lights mounted on armrests, floor mounted electroluminescent lights and self-powered betalights, was evidenced during full-scale postcrash cabin fire tests (38). Another study translated the improved visibility of low level lighting to faster evacuation rate (39). People were able to evacuate in approximately 20 percent less time from a cabin simulator filled with stratified theatrical smoke when seat mounted lighting illuminated the main aisle than from the simulator with conventional ceiling lights. In a third study, the degree of merit of 11 improved emergency lighting systems was evaluated on the basis of illumination, reliability, cost, and other parameters (40).

The final rule, published on October 26, 1984, required floor proximity emergency escape path marking to enable passengers to visually identify the emergency escape path along the cabin aisle and to readily identify each exit by reference only to markings and visual features not more than 4 feet above the floor (9). All in-service airplanes, type certificated after 1958, were required to comply with the new design standards within 2 years, or by November 26, 1986. Issuance of the rule was followed by an advisory circular (AC) to provide guidance material for use for demonstrating compliance with the floor proximity lighting rule (41). The AC clarified, by example, systems that could or would not meet the requirements of the rule. To meet the requirements of 25.812(e)(1) for markings that enable each passenger to visually identify the emergency escape path along the cabin aisle floor, the AC states that the system must provide a reasonable degree of illumination over the entire length of the escape path along the aisle floor. A distant light at an exit that allows the escape path to remain essentially dark would not be acceptable. Also, the requirement to readily identify each exit by reference only to markings and visual features not more than 4 feet above the floor would not be met by a system that provides only general diffused light in the vicinity of the exit or a system which merely marks the fore and aft location of the exit along the aisle floor, and not the exit itself.

CREWMEMBER PROTECTIVE BREATHING EQUIPMENT

Protection of crewmembers against smoke and toxic gases produced by an in-flight fire includes fixed protective breathing equipment (PBE) for flight deck crewmembers and portable PBE for cabin crewmembers. Criteria for design of flight crewmember PBE are contained in TSO-C99 (42) and include requirements for testing masks and/or goggles for smoke leakage. Portable PBE for cabin crewmembers is required for all transport aircraft by July 6, 1989 (10). Basically, a portable PBE must be located at each approved hand-held extinguisher station.

FINAL COMMENTS

In recent years the FAA has issued an unprecedented series of new standards to improve fire safety in transport aircraft. Many of the new standards are products of FAA's research, engineering and development (R, E & D) program. The use of fire blocking layers for seat cushions and low heat/smoke release interior panels are expected to furnish the greatest gains in airliner fire safety from these standards. However, it is unlikely that further improvements in fire safety from even more fireworthy interior materials can be anticipated in the foreseeable future due to the fact that the new, stringent FAA fire test requirements, especially for interior panels, are driving technology to produce suitable composite designs. Exclusive of fuels and fuel systems safety considerations, additional improvements in aircraft fire safety are more likely from current R, E & D activities related to <u>active</u> fire protection, such as cabin water mist fire suppression or enhanced smoke venting.

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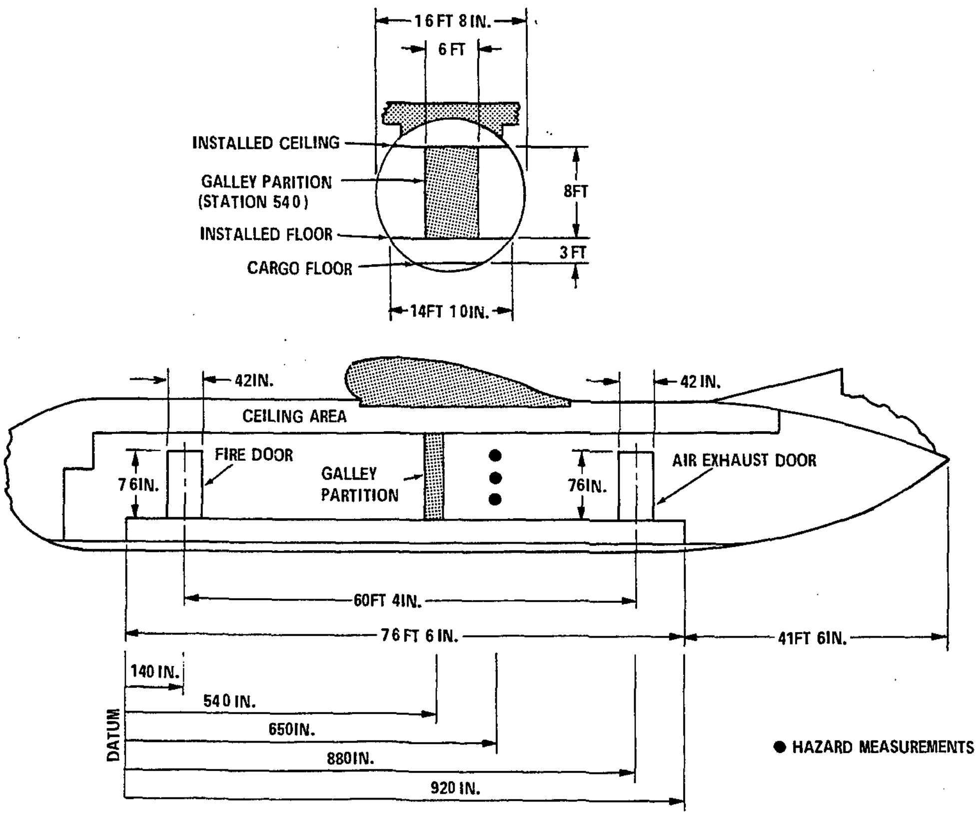

FIGURE 1. C-133 WIDE BODY CABIN FIRE TEST ARTICLE

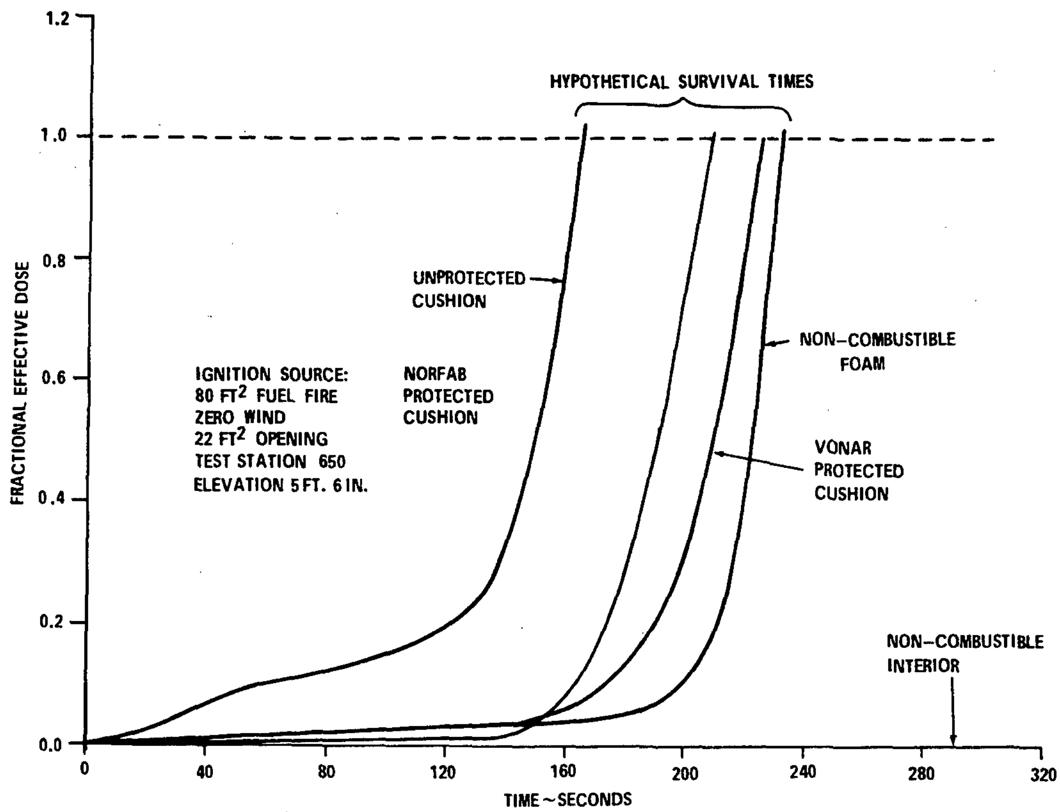

FIGURE 2. EFFECT OF SEAT CUSHION PROTECTION ON FRACTIONAL EFFECTIVE DOSE

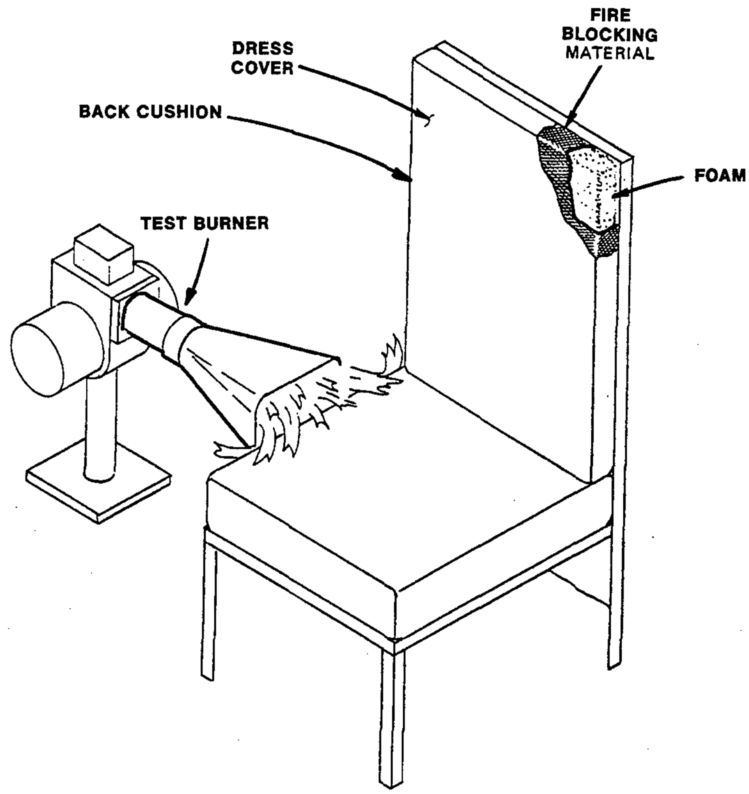

FIGURE 3. FAA SEAT CUSHION FLAMMABILITY TEST APPARATUS

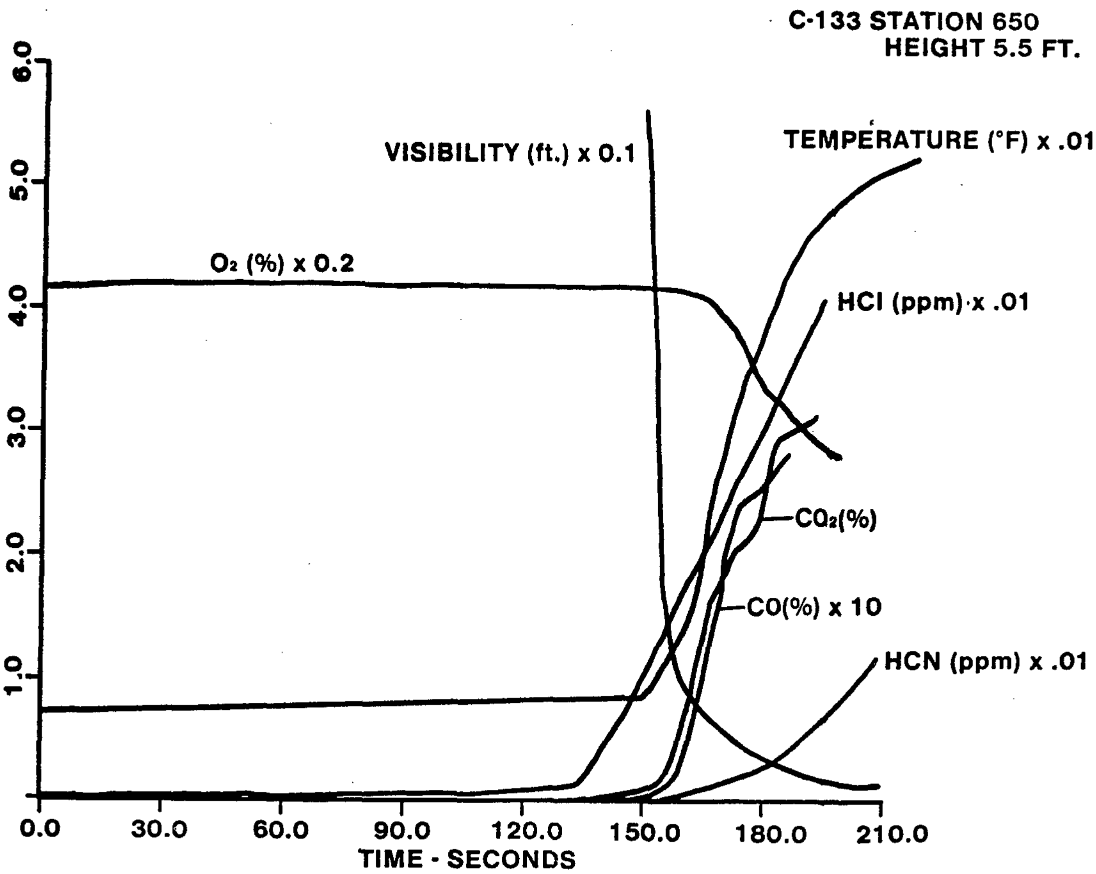

FIGURE 4. TYPICAL C-133 CABIN FIRE HAZARDS PROFILE

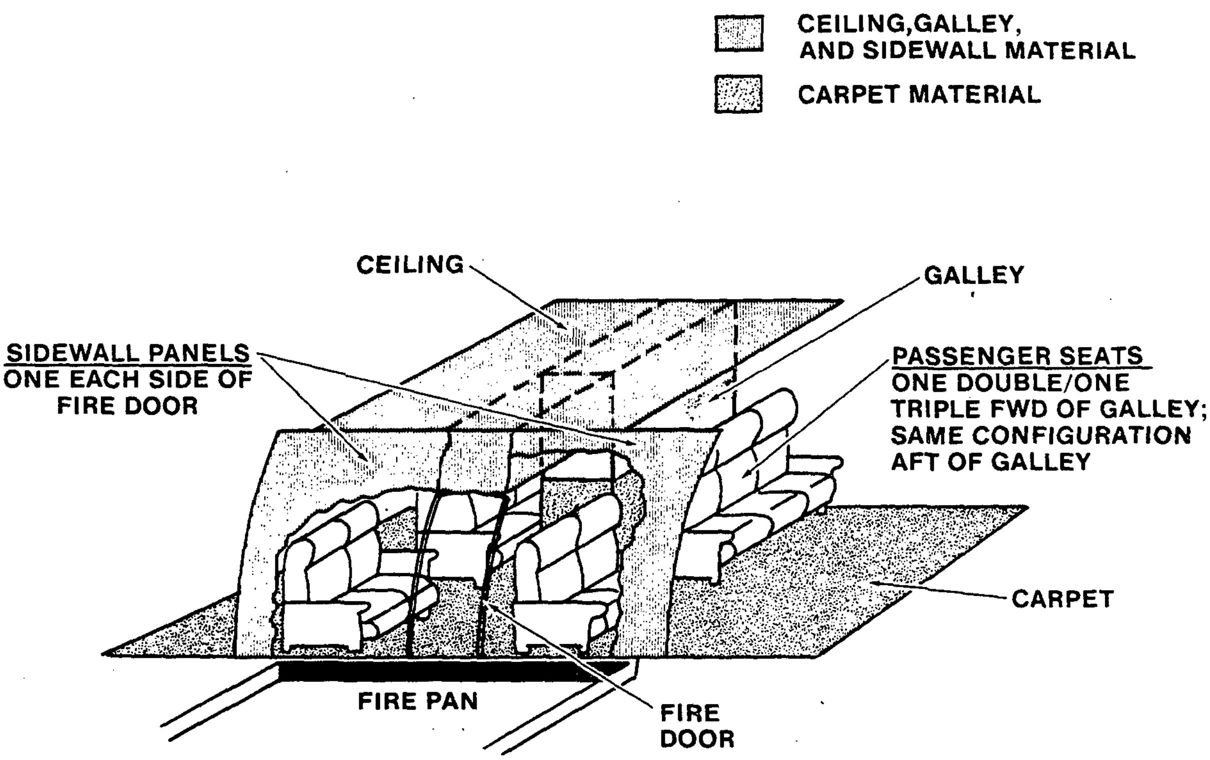

FIGURE 5. POSTCRASH FUEL FIRE OPEN DOOR SCENARIO

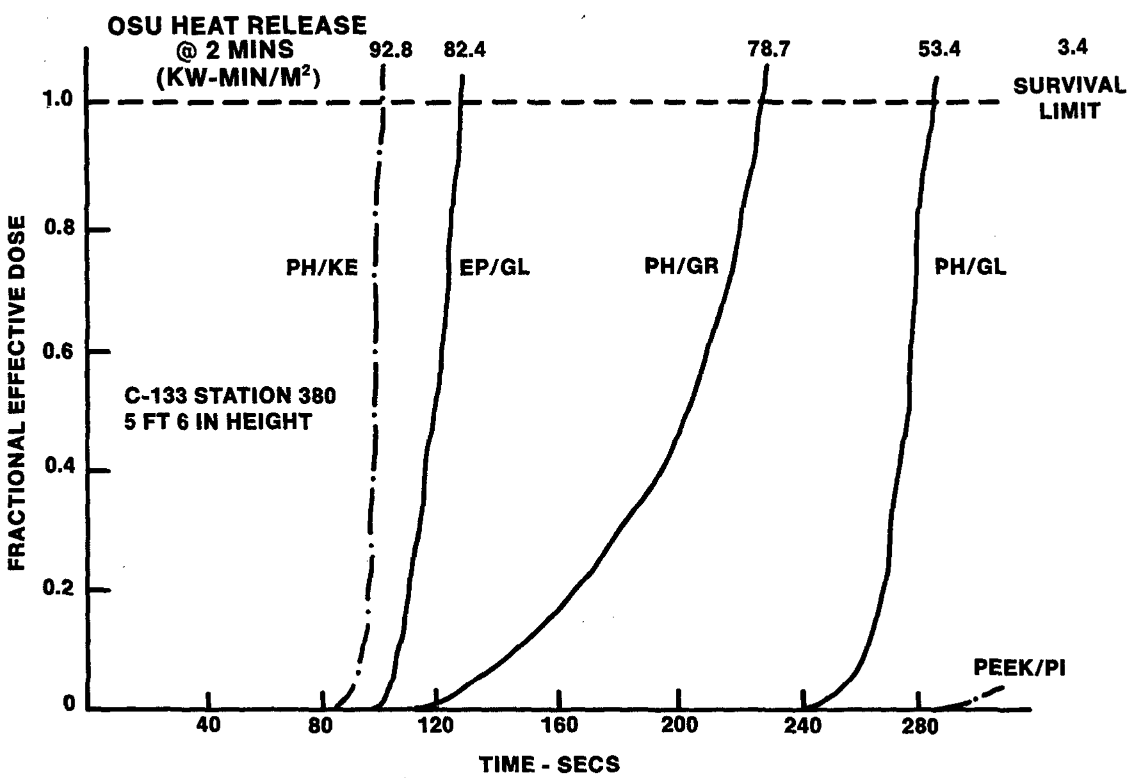

FIGURE 6. EFFECT OF COMPOSITE PANEL DESIGN ON FRACTIONAL EFFECTIVE DOSE

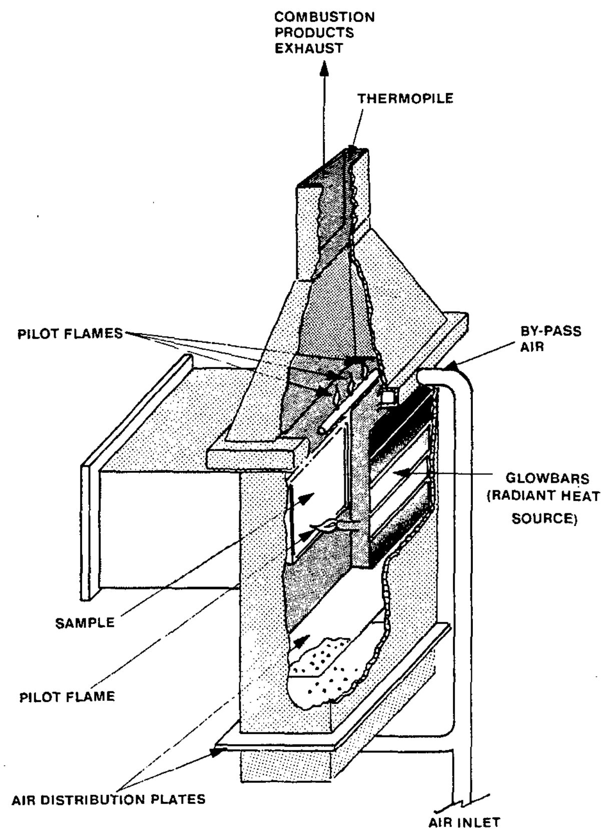

FIGURE 7. FAA OSU RATE OF HEAT RELEASE APPARATUS

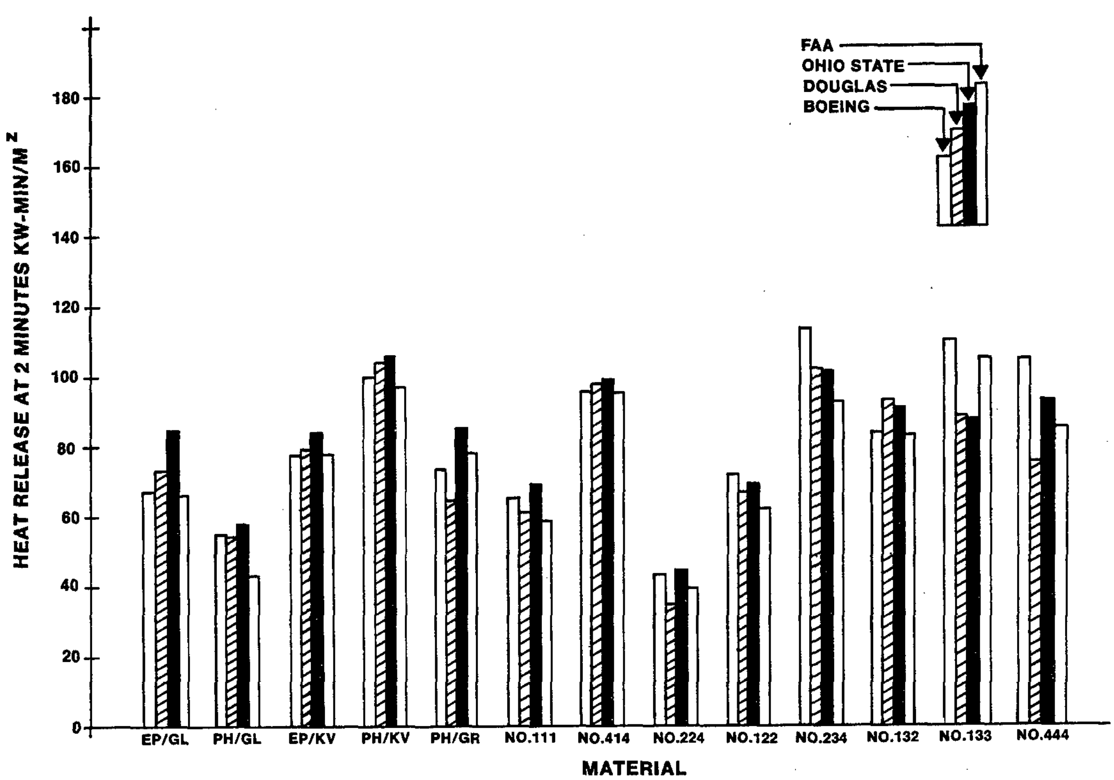

FIGURE 8. REPRODUCIBILITY OF HEAT RELEASE APPARATUS - FAA/AIA THIRD ROUND ROBIN

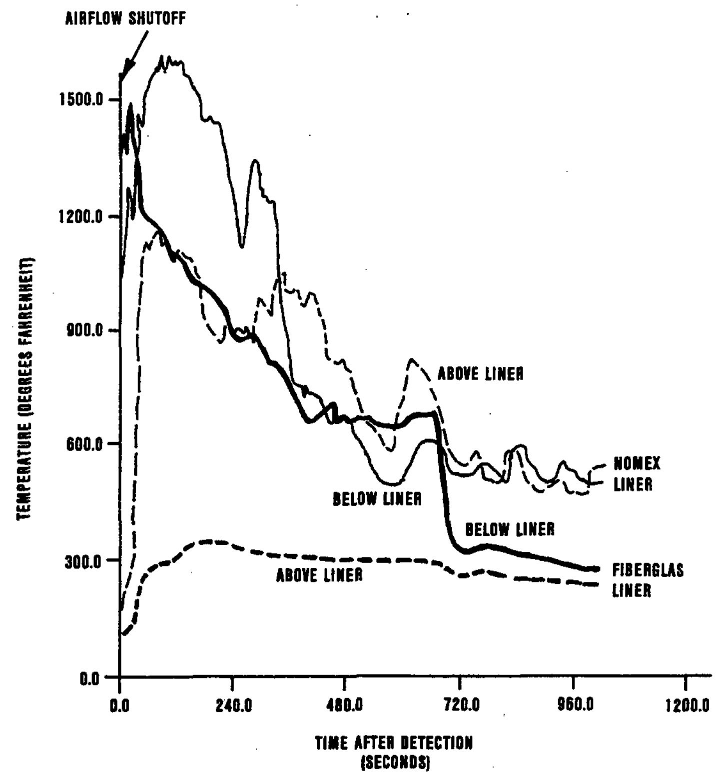

FIGURE 9. CARGO LINER RESISTANCE TO BURNTHROUGH

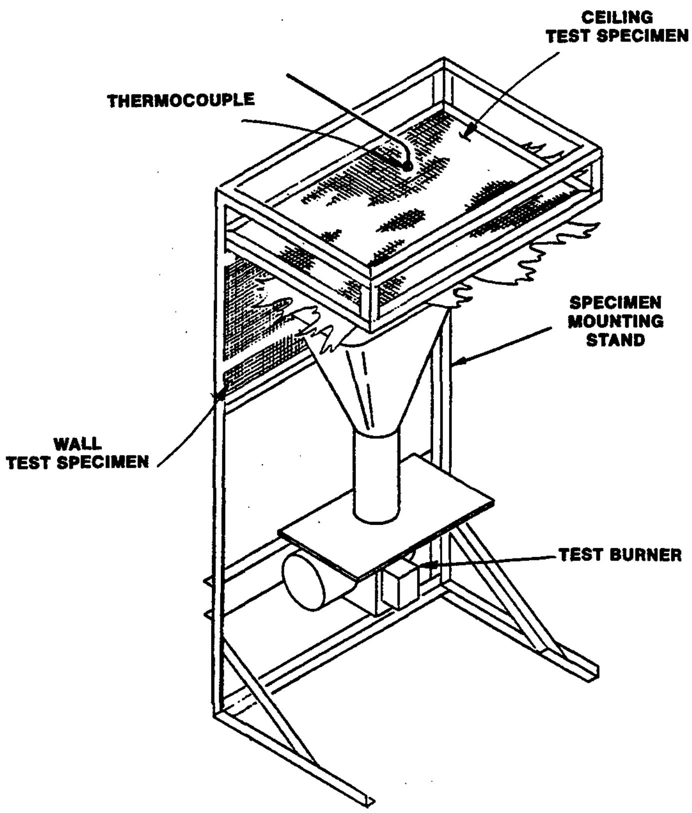

FIGURE 10. FAA CARGO LINER BURNTHROUGH TEST APPARATUS

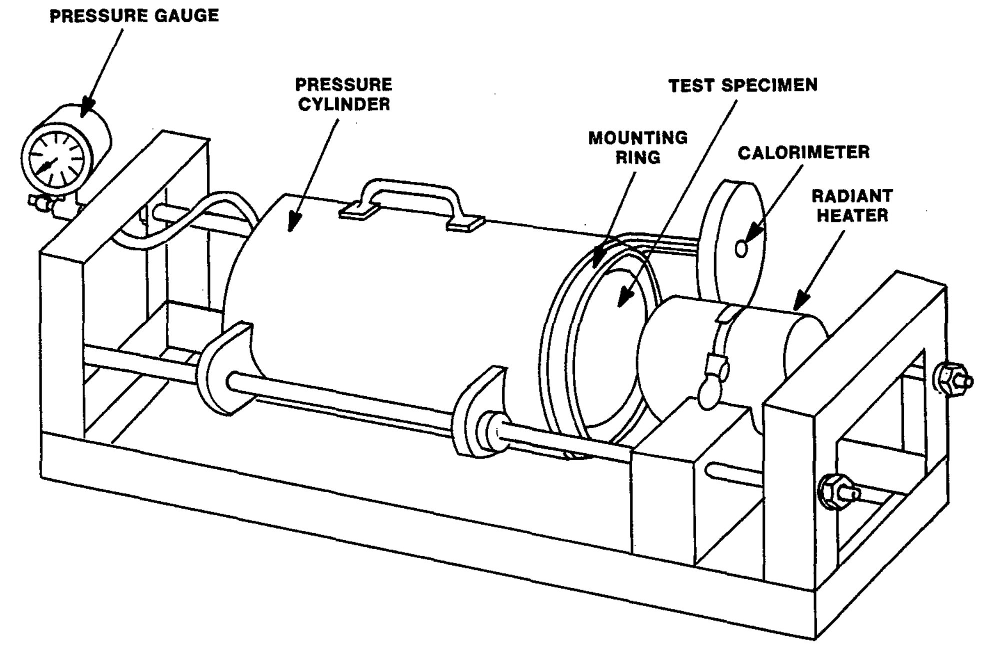

FIGURE 11. FAA EVACUATION SLIDE RADIANT HEAT TEST APPARATUS

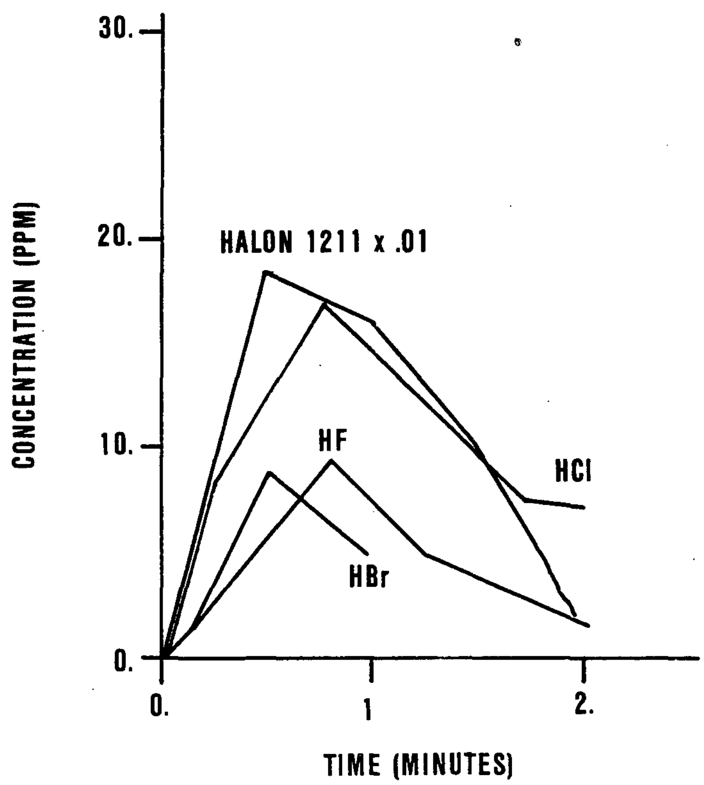

FIGURE 12. CABIN GAS PROFILES DURING HALON 1211 SEAT FIRE EXTINGUISHMENT

DISCUSSION

C. MOSES

Could you clarify which of the new fire-safety technologies you have discussed have been or are being retrofitted into aircraft already in use, and which will only appear in new aircraft?

AUTHOR'S REPLY:

The following fire safety improvements have been retrofitted into the U.S. commercial fleet: seat fire blocking layers, floor proximity lighting, lavatory detectors and extinguishers, halon extinguishers and additional hand-held extinguishers. Retrofit of burnthrough resistant cargo liners is required in approximately one year. The new regulation for low heat/smoke release panels primarily impacts production aircraft and has no retrofit provision; however, at the initial major refurbishment of the cabin interior the usage of low heat/smoke release materials is required.

G. COX

You are using the OSU apparatus to determine rate of heat release. Do you have any plans to move to the cone calorimeter?

AUTHOR'S REPLY:

We are pleased with the reproducibility of the OSU apparatus. Moreover, there are different difficulties in measuring heat release from aircraft materials with the cone calorimeter because of the small readings of oxygen depletion.

A. URAL

Have you consider the in-flight fire scenario where the ignition has taken place behind the wall panels, where the fatalities may arise due to smoke generation.

AUTHOR'S REPLY:

Yes. We are nearing completion of a project that examines the ignitability and fire growth in hidden or inaccessible cabin interiorlocations, such as behind sidewall panels, in lavatories, etc. We have simulated electrical fault ignition sources, overheated wiring and arcing, in these hidden areas and monitored the cabin conditions in a full-scale DC10 test article. Under these ignition conditions, the fire will self extinguish with barely detectable increased temperature or toxic gas levels measured in the cabin . During some tests slight smoke obscuration is measured.

B. TUCKER

The FAA rule requiring floor proximity lighting has been in effect for about 2½ years. However, it appears that most airlines do not include this feature in their passenger safety briefings. Has the FAA considered making mandatory the inclusion of information on floor proximity lighting in passenger briefings and/or safety information brochures.

AUTHOR'S REPLY:

MY own experience is that more airlines are now announcing the presence of floor proximity lighting in the passenger safety briefings. A new Advisory Circular on passenger safety briefings will be issued shortly by FAA with a recommendation that information on floor proximity lighting be included in the passenger briefing. I might also add that the function of floor proximity lighting in an emergency situation would be rather obvious to the passenger.

F. TAYLOR

Have you conducted any tests where you have a hole in the ceiling, either as deliberate venting or by natural burn through?

AUTHOR'S REPLY:

One postcrash fire test was conducted with the ceramic insulation removed in the area of the fuselage ceiling near the fuel fire ignition source. After the 12 min. test, the fuselage ceiling was not penetrated. Planned FAA tests will more thoroughly examine the effect of a fuselage "roof" opening.

BOEING®

Hardening Aircraft Against Terrorist Threats

330

John Kuhn
Project Manager, WABT

Chantal Joubert
Manager,
Aircraft Protection,
Safety and Regulatory

Victor Chen
Project Manager, RBTF

ADPA Conference, Monterey
October 22, 1997

BOEING®

Participation in FAA Aircraft Hardening Program

(Completed)

- Development of Aircraft Structural Response Methodology
- Aircraft Response to Internal Explosive Detonation

(Ongoing)

- Wide Body Aircraft Blast Test
- Reusable Blast Test Fixture

Aircraft	Bombing Attempts	Blast Events Total	Blast Events In flight	Blast Events Catastrophic	% Survive Attempts	% Survive In-flight Blast
Total	81	58	34	15	81%	$\boxed{56\%}$
Narrow-body	58	43	23	12	79%	48%
Wide-body	23	15	11	3	87%	73%
U.S. Events	10	4	1	0	100%	100%

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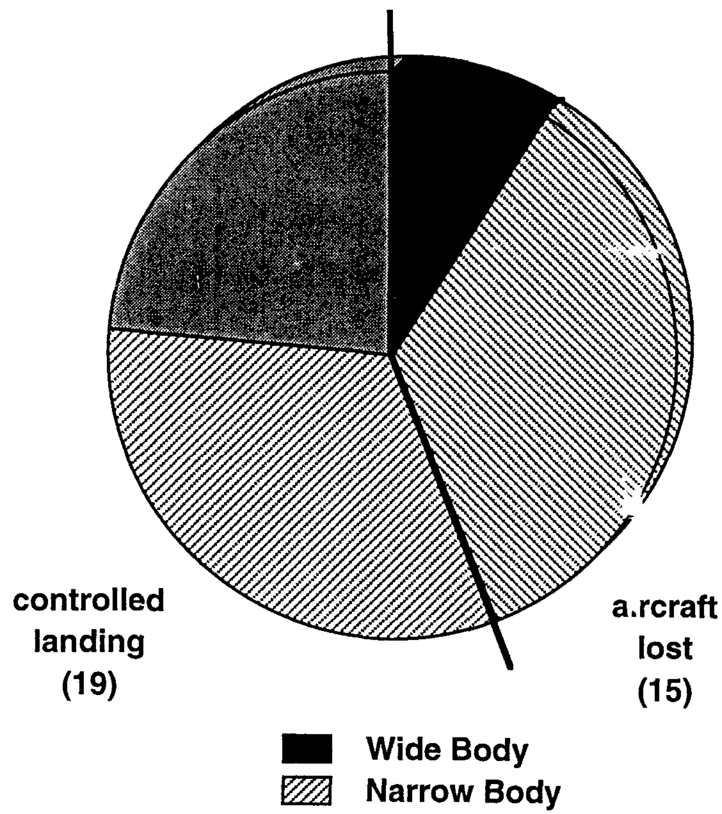
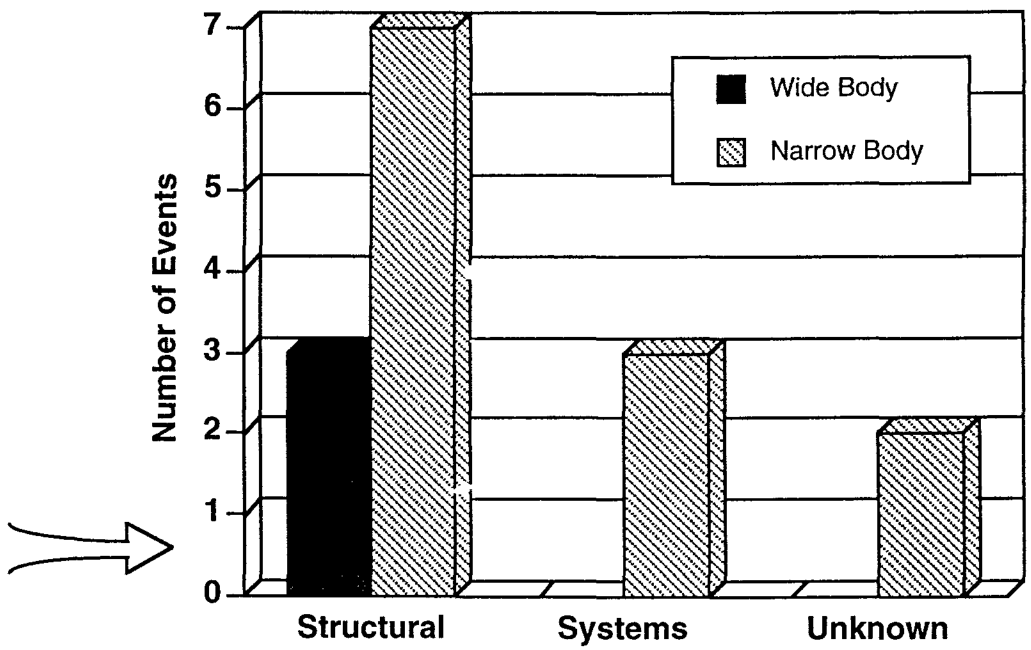
In-Flight Bomb Blast Events
1971 - 1995

Event Outcome of 34 In-Flight Incidents



Failure Modes of 15 Aircraft Lost



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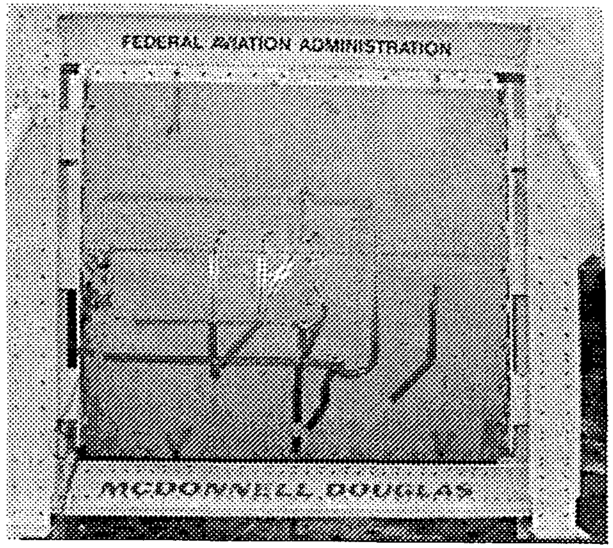
DGPro/Incident Data Summary (#4) (disk)
Mac/pb/9/13/95

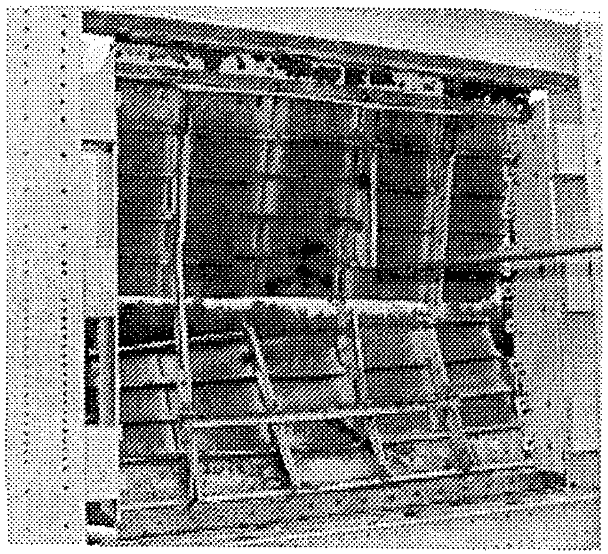
Bombings Against Commercial Aviation
Findings

- Bombings against commercial aviation are a worldwide problem.
  - Has already involved 33 countries and 40 airlines.
- Terrorists have knowledge of new methods to build bombs that may be more difficult to detect.
- 56% of aircraft survive in-flight bombings.
- Wide-body aircraft have a greater inherent tolerance to in flight bombings and 73% survive, compared to 48% of narrow-bodies.
  - Greater internal volume to absorb the blast
  - Greater structural surface area and multiple load paths to dissipate blast loads
  - Greater opportunity for separation of redundant systems

BOEING

Aircraft Hardening Program Materials Properties Database

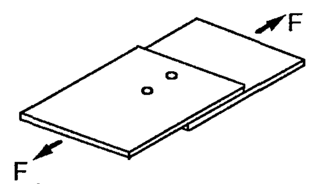




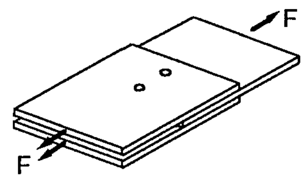
PANEL TESTING

- Mode I fracture toughness for 0.71 in. 2024-T3
- Rate-dependant constitutive relations (full range stress-strain diagrams)

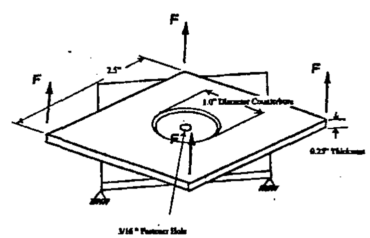
DYNAMIC MATERIALS PROPERTIES



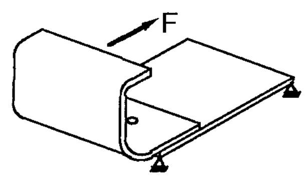
Single Shear



Double Shear



Tension



Peeling load

COMPONENT LEVEL TESTING

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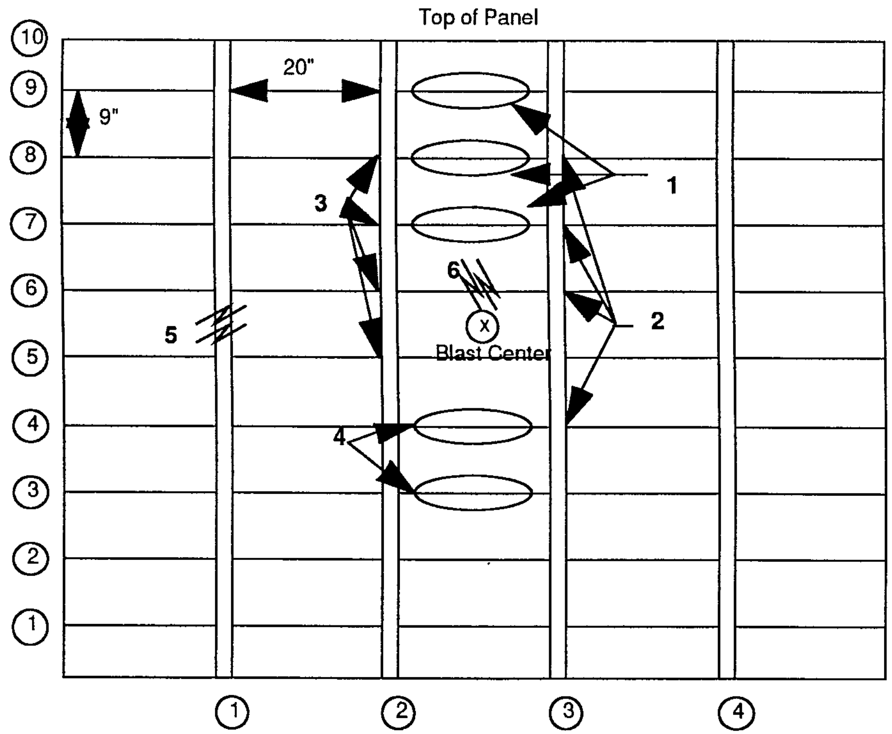
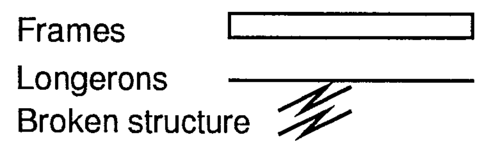
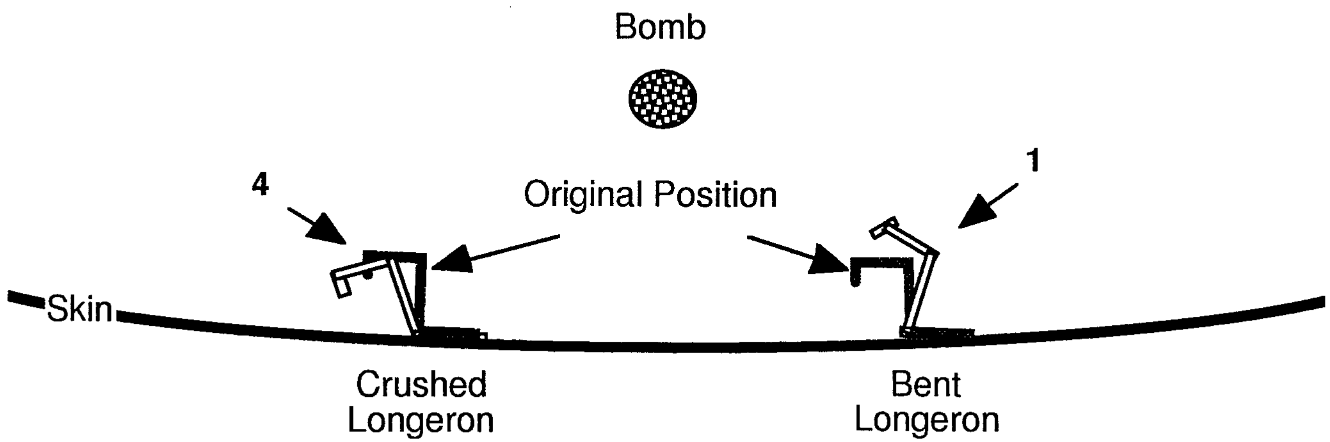


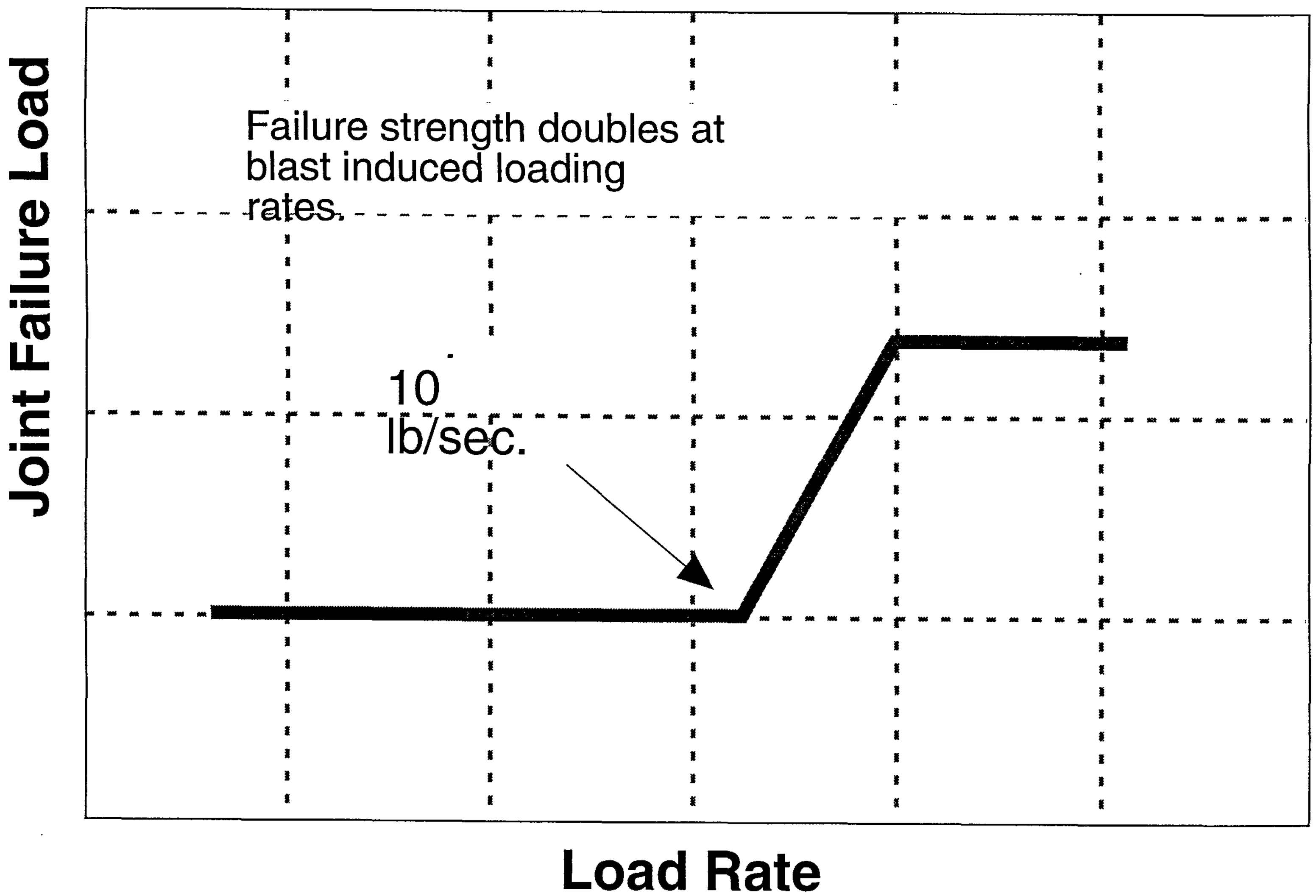


Damage Description :

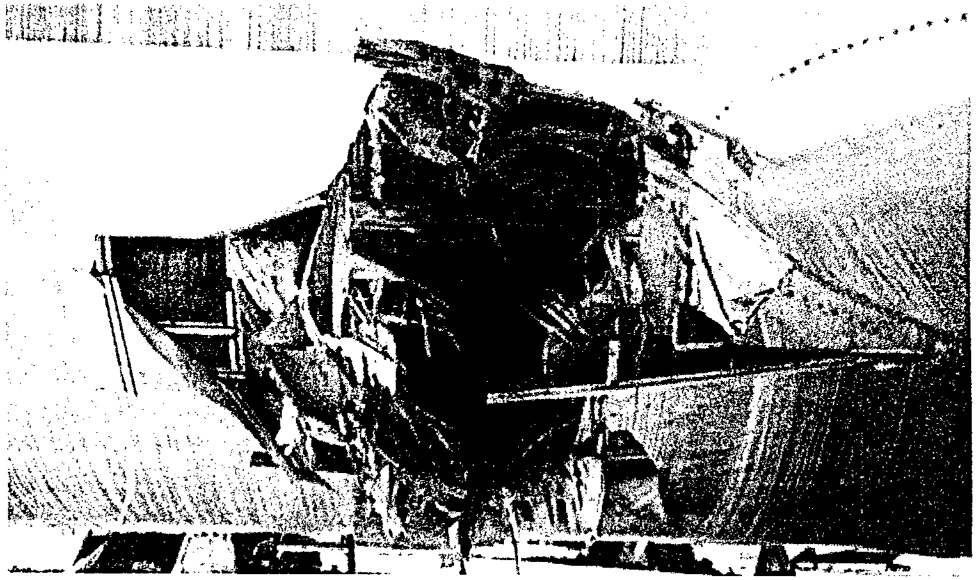
1 Areas where the longerons are bent upward, away from the blast wave.
2 Cleats between the frame and longeron broken.
3 Cleats between the frame and longeron broken.
4 Longerons slightly crushed from blast wave.
5 Frame 1 cracked in Mode III.
6 Longeron 6 also broke in Mode III, small area broken out.



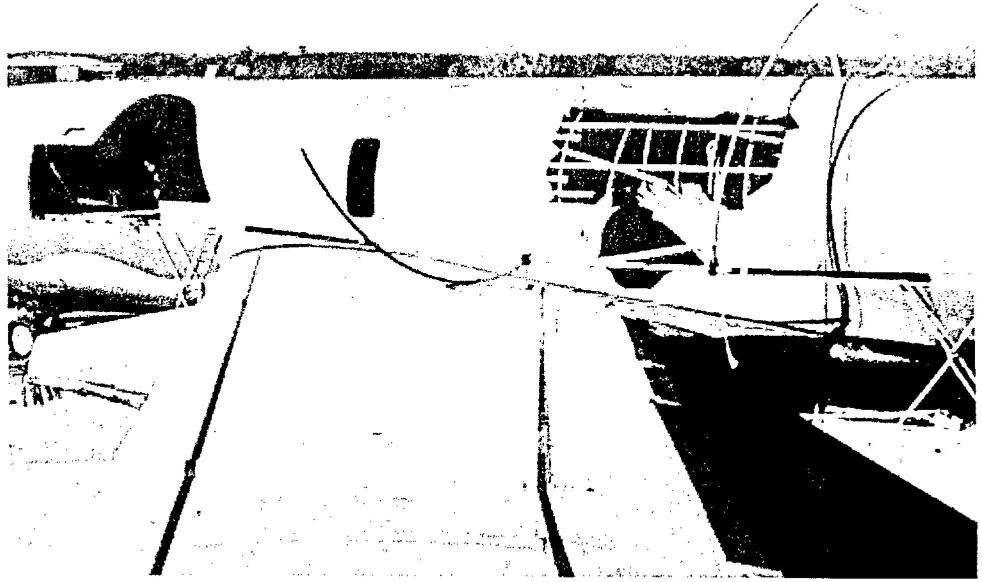
Typical Test Results



Aircraft Hardening Program Aircraft Test Database



B-707 Parametric Tests



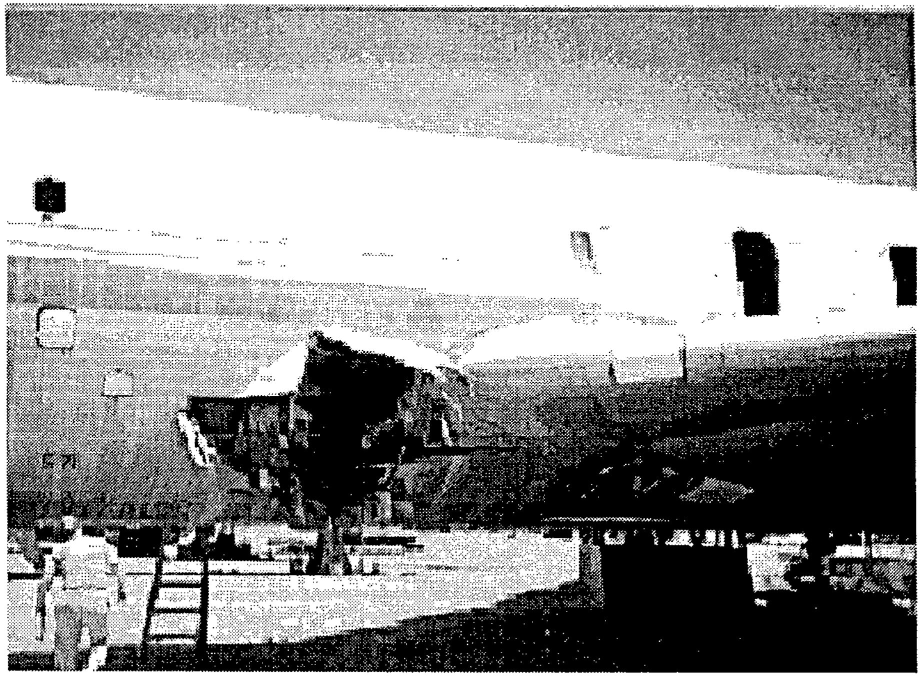
KC-135 Pressurization Tests

C-880 Systems Vulnerability Tests

LD-3 Fragmentation Tests

B-707 Narrow-Body Aircraft Tests
Comparison of Damage Modes

Blast Damage from a Bare Charge



Blast Damage from a Fragmentation Charge
(Single Suitcase)

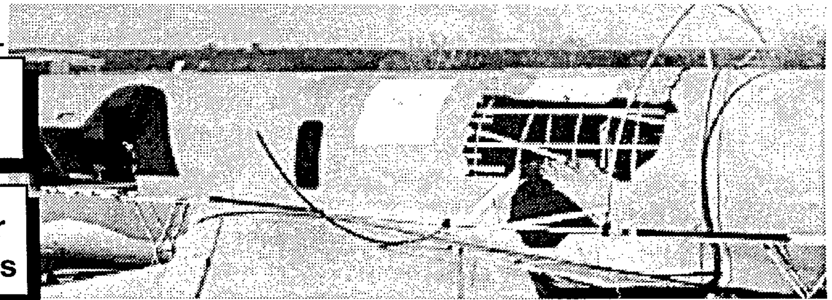
BOEING

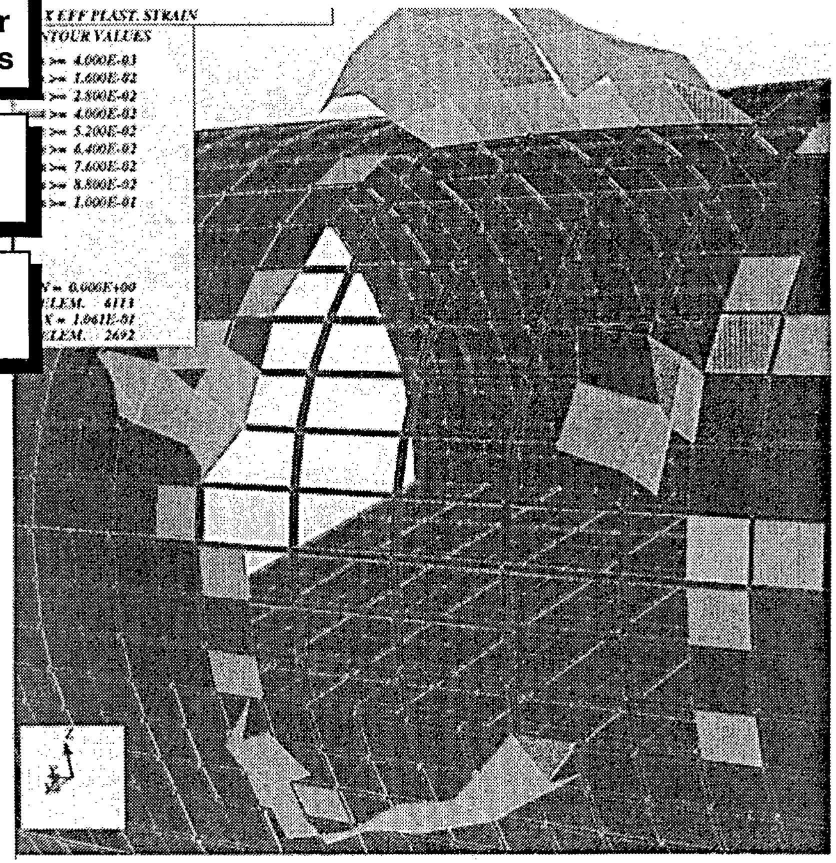
Pressurized vs. Non-Pressurized C-880 Test

LD-3 Threat Characterization Test Series

Integrated Structural Response Methodologies

Pressure Loading	Initial Response	Damage Growth
Empirical Methods		Critical Impulse
INBLAST or eq. PC-codes	Equiv. Static Pressure	Implicit FE codes or close-form solutions
INBLAST or eq. PC-codes	Uncoupled Transient	Implicit FE codes or Freq. Dom. Analysis
Hydrocode (explicit transient FE codes)		Implicit FE codes
Hydrocode: Enhanced PAM-SHOCK/PAM-FLOW		





- Pam codes analysis of KC-135 pressurized bare charge blast tests
- Next step - Add fragmentation effects from LD-3 and luggage

Wide-Body Aircraft Blast Test

L-1011, Mobile Alabama

PROGRAM OBJECTIVE:

To determine the minimum charge size and charge location to cause catastrophic damage, to a wide-body aircraft, from a bomb placed in a LD-3 luggage container.

BOEING

Test Simulates Operational Environment

- Charge placed within luggage within LD-3 Container
- Container surrounded by other containers, all 75% full
- Representative delta pressures (~8.4 psi)

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Test Plan

PRESSURIZED TESTS

ST 1
Near pressure shell away from bulkhead

Repairable ↓

SY 1
Against passenger floor

Repairable ↓

ST 1'
Repeat ST 1 with adjusted charge size

Non-repairable →

UNPRESSURIZED TESTS

ST 2
Against pressure shell using final ST 1 charge size

↓

SY 2
Repeat SY 1

↓

SY 3
Against aft bulkhead using predicted charge size

↓

ST 3
Against fwd bulkhead using final ST 1 charge size

↓

SY 4
Against pressure shell using predicted charge size

↓

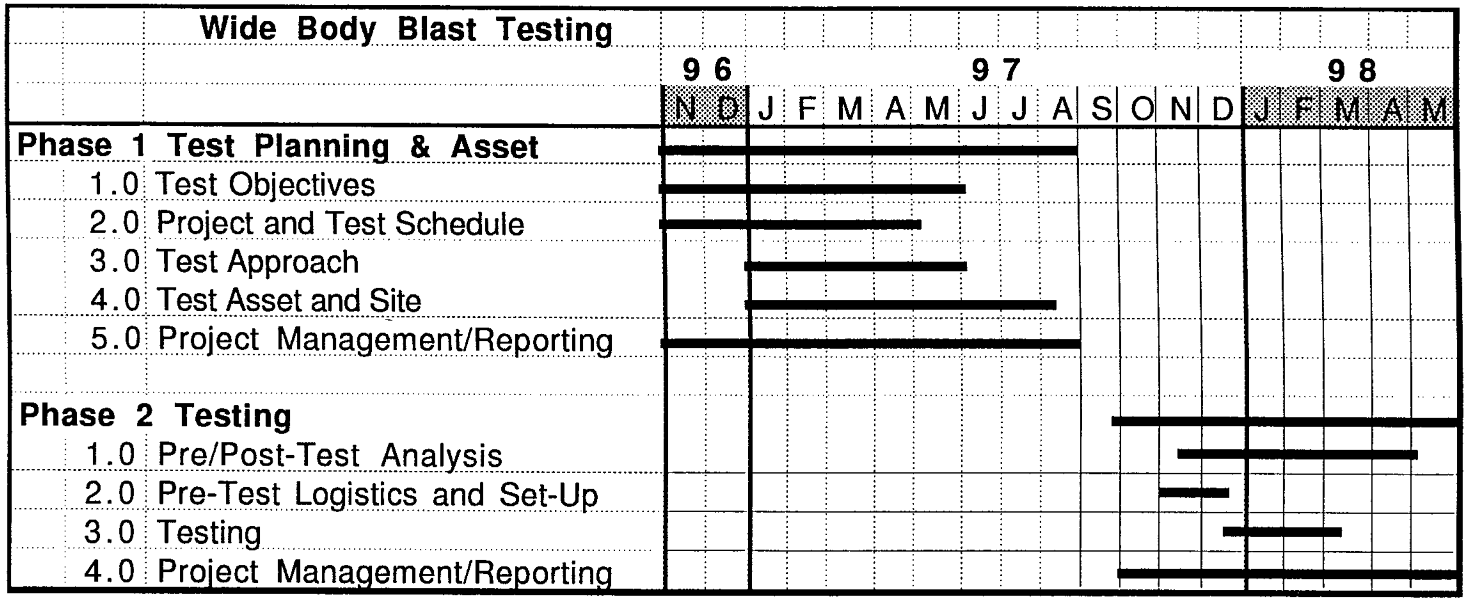
ST 4
Repeat ST 1 without liner using final ST 1 charge size

ST - structural focus

SY - systems focus

BOEING

Program Schedule



<u>Boeing Activities</u>

Aircraft Preparation
Test Configuration
Instrumentation
General site support
Test Documentation and Analysis

<u>FAA Activities</u>

Explosives Handling
Photo/Film

BOEING

Reusable Blast Test Fixture

Objectives

- To provide an asset for gathering repeatable, realistic blast test data.
- To assess/verify hardening concepts; in particular, hardened containers.

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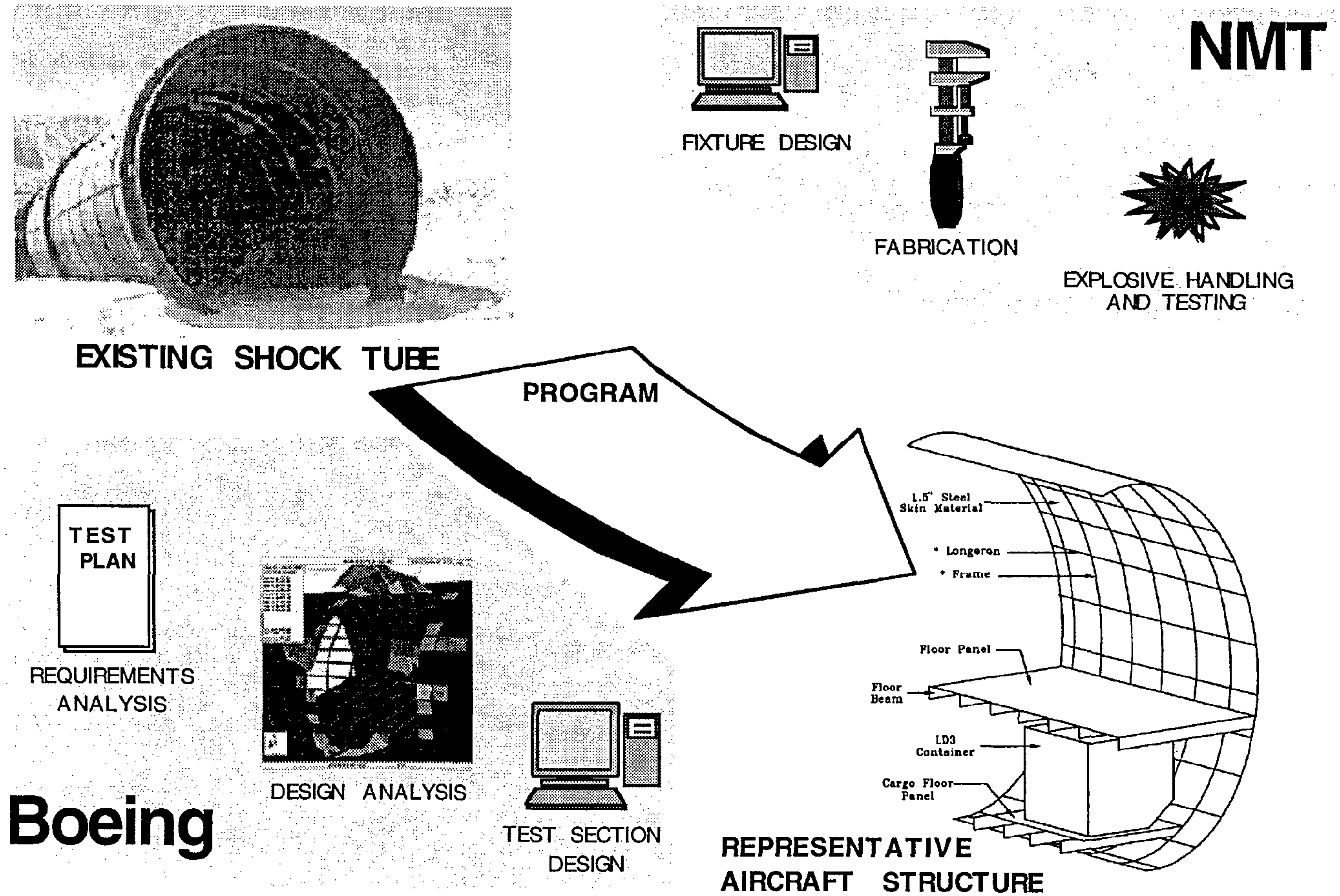
Reusable Blast Test Fixture



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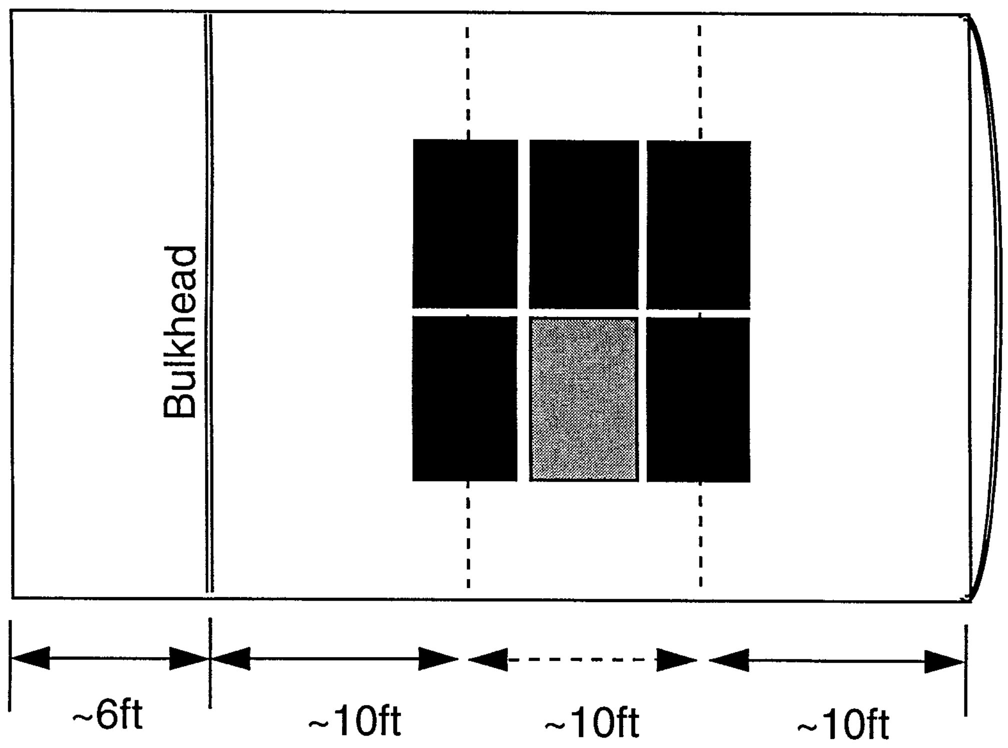
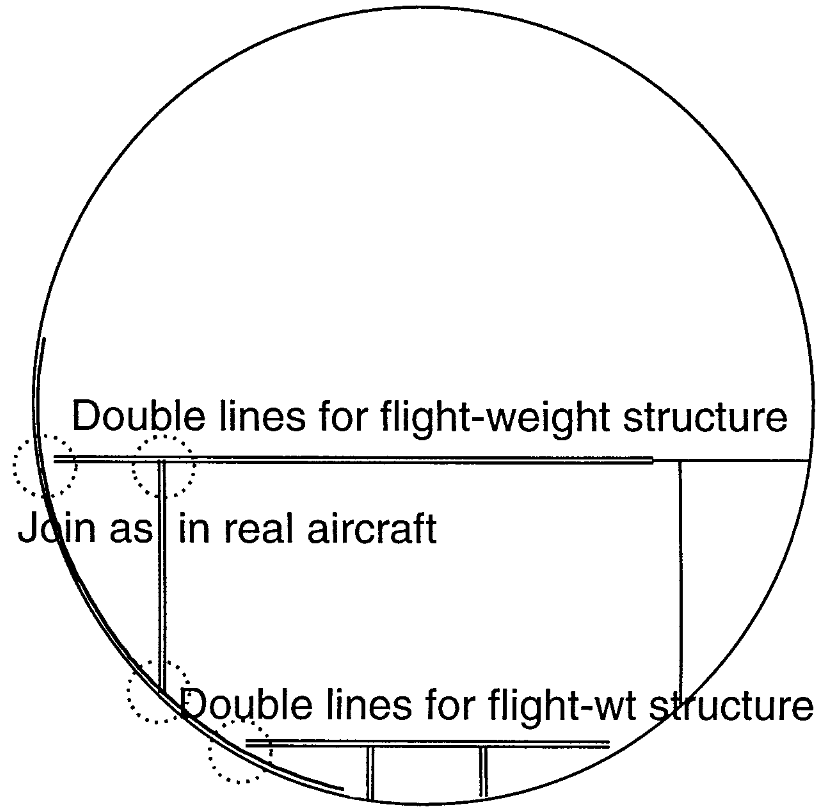
RBTF Basic Design Concept 1

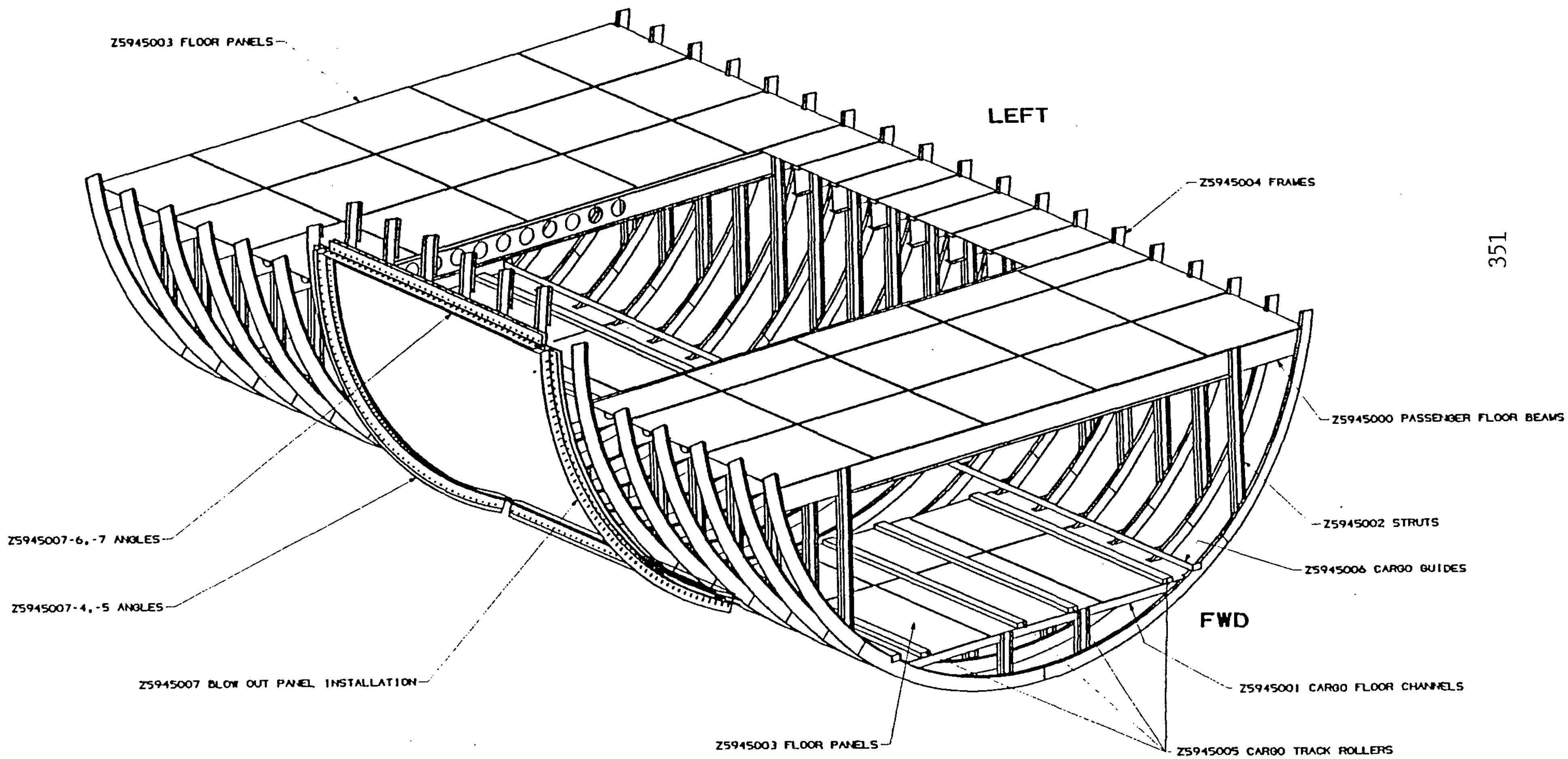
Top View



End View of Test Section



RBTF Basic Design Concept 2



Adding this steel design to an existing 20'-D shock-tube creates a low-cost RBTF. – The opening will be fitted with flight-weight test sections.

Status

- Design Requirements Document Published
- PDR on 2/12/97
  - All parties satisfied with design
  - Decision to initiate fabrication prior to CDR
- Design Drawing and Analysis of Fixture Design Completed
  - Aircraft Section Patch to RBTF with M/S ~ 3
- CDR on 5/9/97
- Anticipate completion of fixture fabrication in October 97

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Summary

- Developing data and tools to properly assess threats and aircraft response to threats.

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NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

**EFFECTS OF DIGITAL AVIONICS SYSTEMS
ON THE SURVIVABILITY
OF MODERN TACTICAL AIRCRAFT**

by

Wade D. Duym

June 1995

Thesis Advisor: Robert E. Ball

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EFFECTS OF DIGITAL AVIONICS SYSTEMS ON THE SURVIVABILITY OF MODERN TACTICAL AIRCRAFT

Wade D. Duym
Commander, United States Navy
B.A., Muskingum College, 1974
M.S., Naval Postgraduate School, 1982

Submitted in partial fulfillment of the
requirements for the degree of

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June 1995

Author: ______________________
Wade D. Duym

Approved by: ______________________
Robert E. Ball, Thesis Advisor

____
Issac I. Kaminer, Second Reader

____
Daniel J. Collins, Chairman
Department of Aeronautics and Astronautics

ABSTRACT

Many modern tactical aircraft incorporate digital avonics systems with federated, centralized or distributed avionics architectures that share data via interconnecting data buses. The design of a digital avionics architecture has an impact on the combat survivability of the aircraft. Survivability in combat is defined as "the capability of the aircraft to avoid and/or withstand a man-made hostile environment." Survivability is made up of two elements; 1) susceptibility, the inability of the aircraft to avoid being damaged by the various elements of the man-made hostile environment, and 2) vulnerability, the ability of the aircraft to withstand the damage caused by the hostile environment. Thus, a tactical aircraft should be designed to avoid being hit and to survive if hit. This thesis explores the survivability advantages and disadvantages inherent in the design of digital avionics system architectures.

TABLE OF CONTENTS

I. INTRODUCTION 1

A. AVIONICS 1

B. SURVIVABILITY 2

C. SURVIVABILITY ASSESSMENT 4

D. THESIS ORGANIZATION 5

II. DIGITAL AVIONICS SYSTEMS BACKGROUND 7

A. DIGITAL AVIONICS 7

B. DIGITAL AVIONICS ARCHITECTURES 8

C. AIRCRAFT ELECTRICAL POWER 11

D. AVIONICS DATA BUSES 12

1. Military Aircraft 12

2. Civil Aircraft 14

E. MICROPROCESSORS 15

F. SENSORS 17

G. AVIONICS DISPLAYS 17

III. SUSCEPTIBILITY EFFECTS 19

A. SUSCEPTIBILITY 19

B. THREAT WARNING 20

C. NOISE JAMMING AND DECEIVING 20

D. SIGNATURE REDUCTION 21

E. EXPENDABLES 22

F. THREAT SUPPRESSION 22

G. TACTICS 23

IV. VULNERABILITY EFFECTS 25

A. VULNERABILITY 25

B. KILL CATEGORIES 25

C. DAMAGE MECHANISMS AND DAMAGE PROCESSES 26

D. VULNERABILITY ASSESSMENT 27

E. CRITICAL COMPONENTS 29

F. LOSS OF FLIGHT CONTROL (ATTRITION) KILL . . . 32
G. LOSS OF ENGINE CONTROL SYSTEMS (MISSION ABORT) KILL 37
H. LOSS OF FLIGHT AVIONICS (MISSION ABORT) KILL . 38
I. LOSS OF TACTICAL SENSOR SYSTEMS (MISSION ABORT) KILL 40
J. ARCHITECTURES 43
1. Federated 43
2. Centralized 44
3. Distributed 46

V. COMPUTING THE VULNERABLE AREA OF AVIONICS COMPONENTS 49
A. VULNERABILITY ASSESSMENT 49
B. "BLACK BOX" VULNERABILITY 51
C. CABLE VULNERABILITY 54

VI. VULNERABILITY REDUCTION IN AVIONICS DESIGN 57
A. VULNERABILITY REDUCTION CONCEPTS 57
1. Component Redundancy (With Separation) . 58
2. Component Location 58
3. Passive Damage Suppression 59
4. Active Damage Suppression 60
5. Component Shielding 60
6. Component Elimination 61
B. CHOICE OF AVIONICS ARCHITECTURE 61
1. Federated 61
2. Centralized 62
3. Distributed 62

VII. CONCLUSIONS 63

LIST OF REFERENCES 65

INITIAL DISTRIBUTION LIST 69

I. INTRODUCTION

A. AVIONICS

Electronic devices and systems that are used in aircraft are commonly referred to as **avionics**. Typical systems within the general class of avionics systems include [Ref. 1: p. 1]:

- Flight control systems (e.g. fly-by-wire controls, autopilot).
- Engine control systems (e.g. Full Authority Digital Electronic Controls (FADEC)).
- Flight avionics systems (e.g. communications, navigation, flight instruments).
- Tactical sensor systems, both passive and active (e.g. radar, electro-optical and electronic warfare).
- Computer systems.

Avionics systems are generally divided between analog and digital types, depending on the manner in which the electronic signal is represented. Older analog avionics systems have largely been replaced by the digital avionics systems that are used in most modern tactical aircraft. These digital avionics systems are characterized by:

- Widespread use of **microprocessors** for computation
- Electronic **sensors** using digital signal processing
- Programmable **displays** such as cathode ray tubes or liquid crystal displays
- Extensive use of high speed **digital data buses.**

There are many design and performance advantages of digital avionics architectures, including: reduced weight,

improved reliability, increased performance, reduced component count, sensor data sharing/sensor fusion, etc. However, the cost of the digital avionics can be high; in modern tactical aircraft the avionics cost is approximately 30-50% of the total aircraft fly-away cost [Ref. 2]. Because of the high cost of modern tactical aircraft, as well as for many other good reasons, tactical aircraft must be survivable if they are to be effective.

B. SURVIVABILITY

A tactical aircraft must be designed with the hostile environment of combat in mind so that the aircraft can survive to complete its mission and return to base. More efficient and capable tactical aircraft should also be more survivable in a hostile environment. Survivability in combat is defined as "the capability of an aircraft to avoid and/or withstand a man-made hostile environment" [Ref. 3: p. 1]. A tactical aircraft should be designed to avoid being hit, and to survive if hit. Survivability is made up of two elements: susceptibility, the inability of the aircraft to avoid being damaged by the various elements of the man-made hostile environment [Ref. 3: p.223]; and vulnerability, the inability of the aircraft to withstand the damage caused by the man-made hostile environment [Ref. 3: p. 135].

The susceptibility of an aircraft is influenced by the aircraft's design, the tactics that are used and the survivability equipment and weapons that it carries. Aircraft designed for combat environments generally incorporate features designed to reduce the likelihood of detection by hostile forces and features designed to reduce the probability of being hit, if detected. One such susceptibility reduction feature is "stealth", which includes signature reduction

techniques applicable to the aircraft's radar, infrared, visual and acoustic signatures. The use of appropriate tactics is also important to mission success.

The survivability goal is to remain undetected, or if detected to be difficult to hit. Once hit, the goal shifts to being able to withstand the hit(s) and still survive. The vulnerability of an aircraft is influenced by the aircraft's design and the choice of survivability features that reduce the amount and/or severity of damage when the aircraft is hit. Typical threat damage mechanisms include penetrators and fragments from missile and gun high explosive warheads, blast and the most recent threat from various high power radiation sources (e.g. electromagnetic pulse, particle beam and laser).

Aircraft designers do not generally choose a digital avionics system architecture because of its effect on the survivability of the aircraft, but rather for its performance advantages. Combat experience gained in the 1950s, 1960s and 1970s in Korea, Southeast Asia and the Middle East shows that aircraft were lost primarily due to damage to the fuel system, engines, flight controls, hydraulic systems and crew [Ref. 3: p 134]. The aircraft then in use did not incorporate extensive digital avionics systems. Modern tactical aircraft which incorporate extensive digital avionics systems were introduced in the mid-1970s and have seen only limited combat use. As a result, we have limited data on the causal factors leading to the loss of modern tactical aircraft and specifically to the contributions of digital avionics systems to aircraft combat survivability.

One characteristic of a modern digital avionics system is its high level of signal integration, as compared to older avionics systems. This integration is a key element in improving the efficiency and capability of the aircraft and is one of the reasons for its improved performance. However, the fact that the majority of the avionics devices are dependent

upon information shared over the data buses is a disadvantage when the data bus information flow is interrupted or corrupted. For example, in the case of fly-by-wire flight control systems on unstable aircraft, where the control of the aircraft is dependent upon maintaining a continuous path between the flight control computer and the control surface servo actuators, combat damage that interrupts or corrupts this information flow could result in the loss of aircraft control. Thus, the choice of a digital avionics architecture can have an impact on the overall combat survivability of the aircraft.

C. SURVIVABILITY ASSESSMENT

Traditional methods of assessing the effects of component failure or damage to an aircraft fall within the discipline of system safety engineering. System safety engineering conducts hazard analyses (also called system safety analyses) of an aircraft in order to identify actual and potential hazards. Hazards are then assessed by considering the hazard severity and potential frequency of occurrence. Once identified and assessed, methods of resolving the hazards are proposed. System safety engineers use critical component analysis tools such as the Fault Tree Analysis (FTA) and the Failure Modes and Effects Analysis (FMEA).

A Fault Tree Analysis (FTA) is a top-down approach which begins with a given undesired event, such as loss of control, and then traces the possible causes of that event [Ref. 4: p. 17]. A Failure Modes and Effects Analysis (FMEA) is a bottom-up approach that identifies and records all possible failure modes of a component or subsystem and determines the effects of these failure modes. The effects are then linked to the ability of the component or subsystem to perform essential

functions [Ref. 4: p. 11]. The FMEA does not specify the cause of the component failure. When failures caused by combat damage are investigated, the process is called a Damage Mode and Effects Analysis (DMEA) [Ref. 3: p. 142]. While it is not necessary to do both, combining the top-down approach of Fault Tree Analysis (FTA) with the bottom-up approach of the Failure Modes and Effects Analysis (FMEA) can give a representative picture of the impact of various component failures. After an FTA and/or FMEA has been conducted, a Vulnerability Assessment (VA) of the aircraft can be made.

A Vulnerability Assessment is the process of assigning numerical values for the various measures of vulnerability. Vulnerable area, defined as that area on the aircraft which if hit would cause a kill of the aircraft, is one such measure [Ref 3: p.153]. Numerical assessment can be done through the use of computer programs, such as the Computation of Vulnerable Area and Repair Time (COVART) program [Ref. 5]. COVART is a product of the Joint Technical Coordinating Group for Munitions Effectiveness, Aerial Target Vulnerability Working Group, and is used to determine the vulnerable area of aircraft damaged by the impact of single kinetic-energy penetrators.

D. THESIS ORGANIZATION

The contributions of modern digital avionics systems to the survivability of tactical aircraft are examined in this thesis. Each of the following systems within the general class of avionics is discussed:

- Flight control systems
- Engine control systems
- Flight avionics systems

- Tactical sensor systems
- Computer systems

Chapter II provides background information on digital avionics systems and architectures, summarizing their key features and characteristics. The focus of Chapters III and IV is on the contributions of the avionics systems and architectures to aircraft susceptibility and vulnerability, respectively. Chapter V discusses a proposed methodology by which the contributions of an avionics system to the vulnerable area of a tactical aircraft can be computed. Chapter VI contains design guidance and recommendations to reduce the vulnerability of digital avionics systems in order to increase a tactical aircraft's combat survivability.

II. DIGITAL AVIONICS SYSTEMS BACKGROUND

A. DIGITAL AVIONICS

The commonly applied definition of **avionics** includes all analog and digital electronic devices that are used in aircraft. Older analog systems that use variable resistance, capacitance and inductance and have an analog output signal are no longer the basis for new designs. Most modern aircraft use a digital avionics system that is made up of sensors, displays, data buses and microprocessors that are combined to perform various operations on binary electronic signals.

The binary signals are typically shown as **yes** equals one, or positive voltage, and **no** equals zero, or negative voltage, although the reverse is also possible. The output of the system operations is a string of ones and zeroes, encoded in accordance with a specific signal protocol that travels throughout the aircraft on digital data buses.

In a digital avionics architecture, the tasks are functionally allocated between the software, hardware and crew [Ref. 6: p. 8]. The level of integration is dependent upon the choice of avionics architecture, the size of the crew and the number of avionics systems to be integrated. The design choice of a digital avionics system is primarily important because of the additional capabilities, such as weapons, sensors or displays, that can be utilized by the aircraft and crew. Digital avionics systems can contribute [Ref. 6]:

- advanced sensors, processors and displays
- expert systems
- sensor fusion/weaponization

* improved command, control, communications and navigation

to the overall capabilities of the tactical aircraft.

B. DIGITAL AVIONICS ARCHITECTURES

Three main types of digital avionics architectures are available to the designer; federated, centralized (or integrated) and distributed [Ref. 6: p. 119]. Each type has specific characteristics, advantages and disadvantages, with the optimum choice dependent upon aircraft and mission requirements.

The majority of current generation aircraft (e.g. F-16, F/A-18) incorporate a federated architecture. Many earlier generation aircraft (e.g. F-14, A-10) are being retrofitted with a hybrid federated architecture. Future generation aircraft (e.g. F-22, JAST derivatives) will probably incorporate either a centralized architecture or a distributed architecture.

The federated architecture is shown in Figure 1. "A federated architecture is characterized by each major system, ..., sharing input and sensor data from a common set of hardware, and consequently sharing their computed results over data buses [Ref. 6: p. 119]." This design allows for relatively independent systems which combine in using a common data base. As a result, there is a degree of compartmentalization inherent in this architecture. A federated system in a military aircraft typically shares data over the MIL-STD-1553B data bus.

Some future generation aircraft will probably incorporate the centralized architecture shown in Figure 2. "A centralized architecture is characterized by signal conditioning and computations taking place in one or more

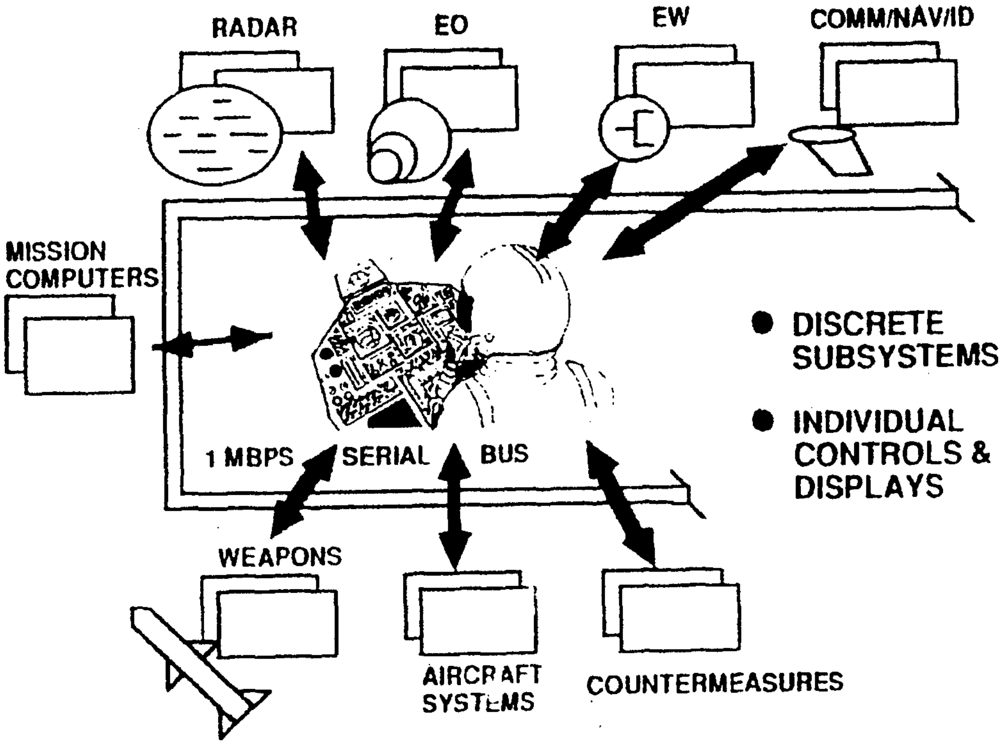

Figure 1. Federated Avionics Architecture, after Ref. [1]

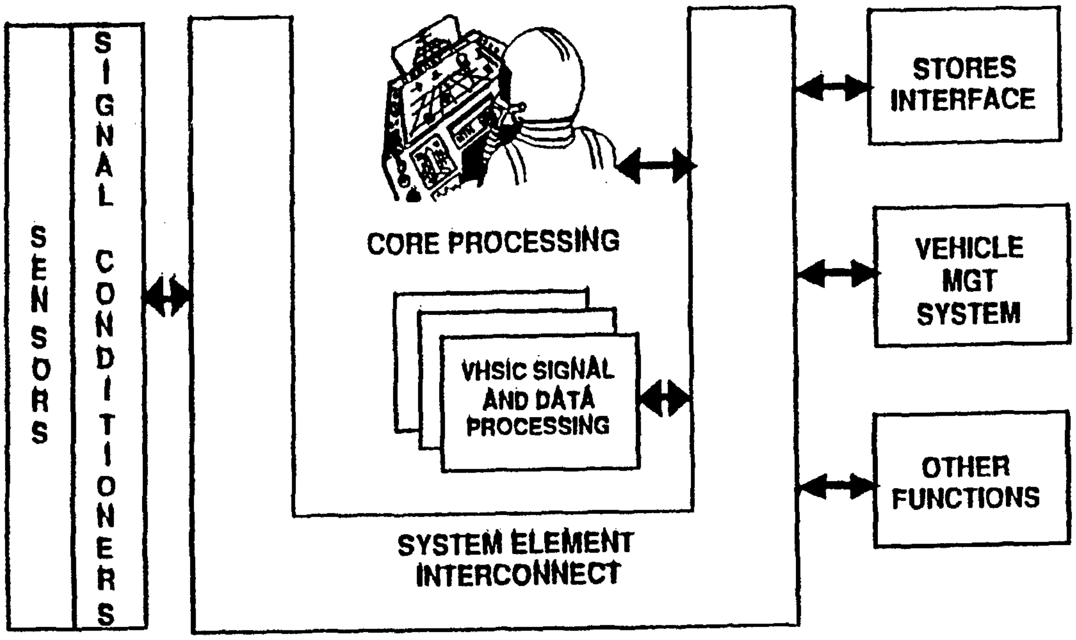

Figure 2. Centralized (Integrated) Architecture, from Ref [1]

computers...located in the avionics bay with sensor and command signals transmitted over data buses [Ref. 6: p.120]." This type may also be called an integrated architecture [Ref. 1: p. 6]. A centralized system in a military aircraft may use several different kinds of data buses, depending on the performance requirements.

The distributed architecture that is being evaluated for use in future tactical aircraft combines many of the features of both the federated and centralized architectures, as shown in Figure 3. "A distributed architecture has multiple processors throughout the aircraft that are assigned computing and control tasks in real time by executive software as a function of mission phase and/or system status [Ref. 6: p.120] " These distributed processors may perform significant amounts of signal processing at or near the sensors or actuators. A distributed system in a military aircraft is likely to use several high performance digital data buses, possibly based on civil computer networking standards.

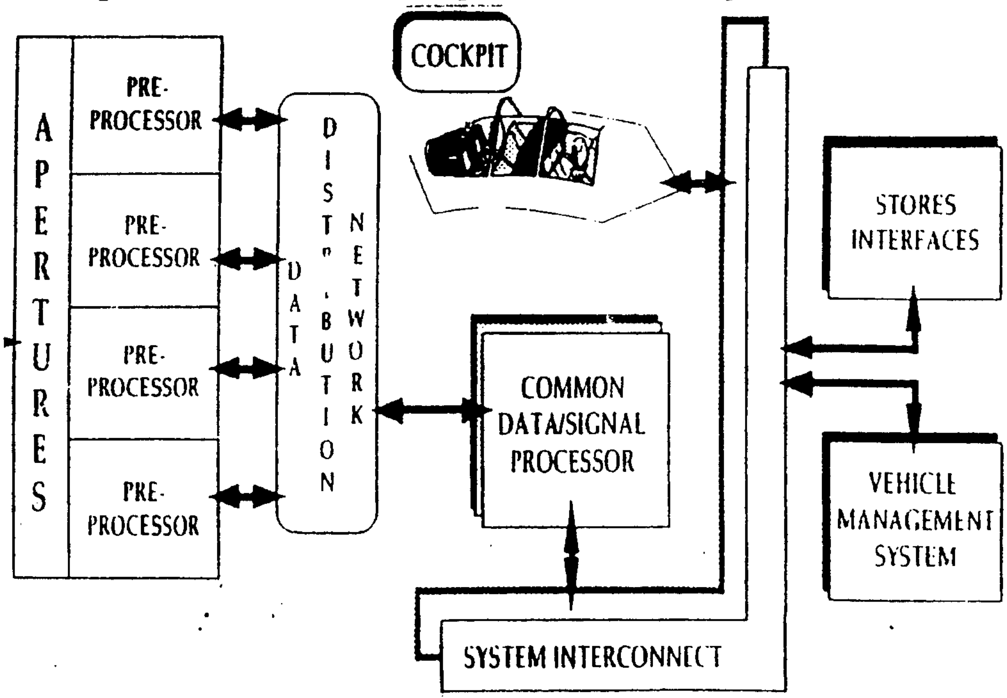

Figure 3. Distributed Architecture, from Ref.[1]

C. AIRCRAFT ELECTRICAL POWER

In all digital avionics system architectures, there is an assumption of reliable, uninterrupted electrical power. With analog avionics systems, it was relatively easy to design systems that were insensitive to interruptions in aircraft power and tolerant of voltage or frequency variations. The aircraft power system for modern digital avionics systems is not so easy to design. Most digital systems, especially microprocessors, are highly intolerant of interruptions in power and many are sensitive to variations in supply voltage and frequency. The requirements of MIL-STD-704: Aircraft Electrical Power Characteristics [Ref. 7] for military aircraft, or RTCA document DO-160: Environmental Conditions [Ref. 8] for commercial aircraft, detail the aircraft electrical power environment.

These two standards describe the over and under-voltage conditions, frequency variations, power interruptions and other conditions that the designer must accommodate. Of particular interest to the designer is the assumption that military aircraft electrical power systems may exhibit power interruptions of up to 50ms under transfer conditions [Ref. 6: p. 79], while power interrupts of up to 1s can be expected in civil aircraft [Ref 6: p. 81]. This is a significant design driver, especially for volatile microprocessor memory. The use of static random access memory (SRAM), which retains its contents only so long as power is applied, usually causes a designer to specify an alternate or back-up to the aircraft power supply. Some types of dynamic random access memory (DRAM), which use capacitance to retain memory contents and which depend on periodic refresh cycles, may also cause the designer to consider an alternate or back-up power supply. The criticality of the avionics function determines whether a given device requires uninterrupted power or not.

The aircraft electrical loads are characterized as either critical, essential or utility [Ref. 6: p. 88]. Critical loads include flight control systems, cockpit flight instruments and cockpit displays. The nature of these systems demands that multiple, redundant power buses be provided and that provisions for uninterruptable power be made available. Avionics systems of lesser criticality are typically referred to as essential loads, examples of which are the tactical sensors. Systems that are not essential to safe flight, such as galley equipment or entertainment systems, are usually referred to as utility loads. Redundant power generation and storage systems for the critical and essential loads are typically specified in order to obtain the required reliability of the avionics system and to provide backups in case of malfunction or damage.

D. AVIONICS DATA BUSES

1. Military Aircraft

The digital avionics data buses may be thought of as the nervous system of the aircraft, with multiplexed signals being shared between systems connected by the data bus. Current military aircraft typically incorporate the MIL-STD-1553B data bus, with some aircraft incorporating the fiber-optic cable version of the 1553B protocol, the MIL-STD-1773 data bus. Future tactical aircraft are likely to incorporate the High Speed Data Bus (HSDB), probably in combination with the 1553B and 1773 data buses. It is also likely that avionics equipment incorporating either of the commercial data bus standards, ARINC 429 or ARINC 629, will be used on military aircraft.

The MIL-STD-1553B data bus is characterized by the use of time-division multiplexing and a bus controller. The bus controller functions as a "traffic cop" to prevent two or more devices from transmitting simultaneously. If the bus controller fails, the data bus is rendered inoperative. The data bus protocol and the message formats are called out in the specification document [Ref. 9].

The 1553B operates at the relatively slow data transfer rate of 1 MBit/s. In order to increase reliability and reduce electromagnetic interference, the 1553B data bus uses a twisted, shielded pair of wire cables which is routed through the aircraft. Typical cable design is shown in Figure 4. Depending on the criticality of the function, some aircraft use as many as four 1553B data buses in parallel.

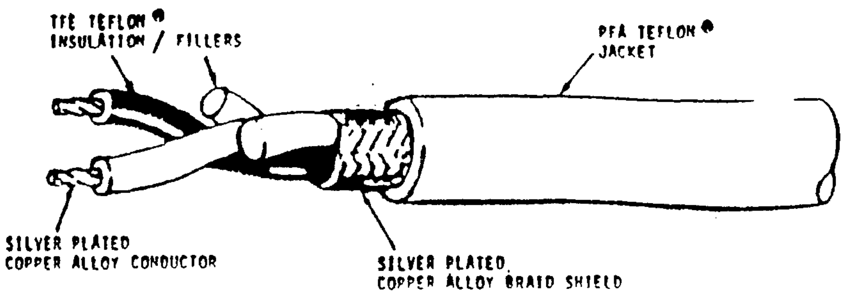

Figure 4, MIL-STD-1553B Cable, after Ref [9]

The DOD-STD-1773 digital data bus [Ref. 10] is a fiber-optic cable implementation of the same data bus protocol used in the 1553B. The intent of the change to fiber-optic cables was to reduce the possibility of electromagnetic interference and to reduce weight. The current implementation is restricted to 1 MBit/s, although the possibility exists to increase the data transfer rate of the 1773 data bus to 8 MBit/s in the enhanced mode. The 1773 data bus incorporates most of the features of the 1553B, including a bus controller,

with the twisted, shielded cable replaced by a fiber-optic cable, such as Figure 5.

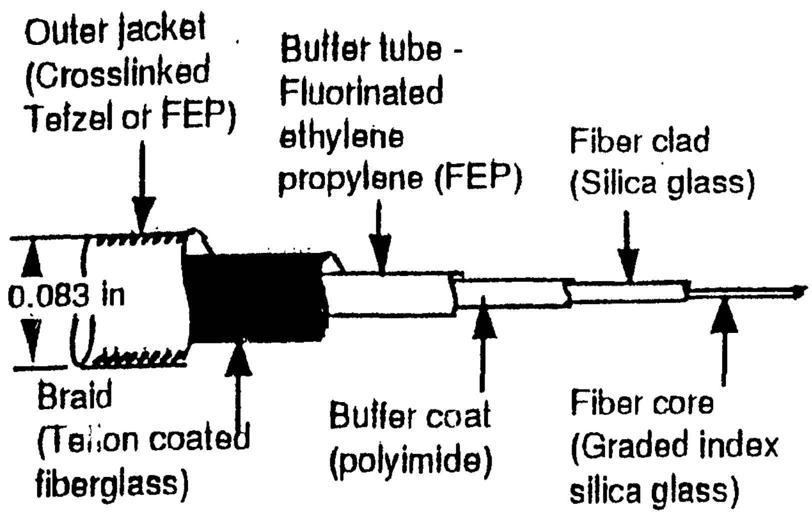

Figure 5, DOD-STD-1773 Fiber-Optic Cable, after Ref [10]

The latest military standard digital data bus is the High Speed Data Bus (HSDB), which was developed by the Air Force to provide a much increased rate of data transmission [Ref. 11]. The HSDB can transmit data at up to 50 MBit/s and can use several different bus topologies in either the conventional twisted, shielded pair or fiber-optic cable implementations. A key design feature of the HSDB is a "token passing" control architecture, which removes the requirement for a bus controller. This is a key design advantage of the HSDB over the earlier MIL-STD 1553B or DOD-STD-1773 data bus designs because a single point of failure (kill) has been avoided.

2. Civil Aircraft

The civil standards for digital data buses in transport aircraft are the ARINC 429 [Ref. 12] and ARINC 629 [Ref 13]. The ARINC 429 digital data bus is a simplex bus in which there

is only one transmitter but multiple receivers. This design choice avoids the use of a bus controller, although it does require the use of multiple data buses. There is a requirement for a dedicated ARINC 429 data bus for each pair of avionics devices that must transfer information to one another. The ARINC 429 uses a twisted, shielded pair wire cable very similar to that used by the MIL-STD-1553B. The rate of data transmission is slower than the 1553B, at either 12 to 14.5 KBit/s (low speed) or 100 KBit/s (high speed). Because the ARINC 429 is a simplex bus with a single transmitter, there are multiple ARINC 429 data buses. This increases reliability and eases certification at the cost of additional weight and complexity.

The latest civil digital data bus standard is the ARINC 629. This is a multi-transmitter data bus that also does not require a data bus controller. In the ARINC 629 design, each avionics device is granted autonomous access to the bus based on a complex timing scheme. The rate of data transmission, at 2 MBit/s, is faster than the 1553B and the ARINC 629 can use any one of three cable designs: wire, with either inductive or voltage coupling and optical fiber. The use of inductive coupling avoids the weight penalty associated with cable shielding, since the data bus signals are current-coupled instead of voltage-coupled. This data bus has been chosen for use in the Boeing 777.

E. MICROPROCESSORS

Recent advances in microelectronic technology have made it possible to use computers as an integral part of avionics systems. Miniaturized digital computers are typically referred to as microprocessors, or even as "chips", because they are usually contained on a single integrated circuit

(I.C.) chip. They are used for many different functions (e.g. numeric calculations, control, graphics displays and signal processing). Because of their small size and robust capability, these devices are found in nearly all avionics systems.

Microprocessors, as a group, are generally understood to include both general purpose computers and digital signal processors. Within general purpose computers, microprocessors are divided into Complex Instruction Set Computer (CISC) and Reduced Instruction Set Computer (RISC) types. [Ref. 1: p. 70]

The most common type of microprocessor is the CISC chip, characterized by the various MIL-STD-1750A 16-bit computer chips and the Intel 80X86 series chips that are popular in personal computers. These are general purpose microprocessors which incorporate the hardware and software needed to carry out many different complex operations. Their internal operations may take one, two or even several cycles to complete. CISC computers are very flexible and powerful and serve as the "brains" of many avionics systems.

An emerging microprocessor type is the RISC chip, characterized by the Sun SPARC and the Motorola Power PC chips. These are general purpose microprocessors whose design has been optimized to support completion of internal tasks within a single cycle. RISC computers are more efficient than the CISC design, although they require software that is optimized for the smaller number of instructions. RISC chips have found significant use as the "engines" for work stations and are finding uses aboard aircraft avionics systems.

The third type of microprocessor is the Digital Signal Processing (DSP) chip. The DSP chip is usually dedicated to signal processing applications where extremely efficient input/output capability is important due to the sheer volume of data to be processed. DSP chips are commonly found in avionics sensor systems (e.g. radars, acoustic processors).

F. SENSORS

There are many avionics devices that detect and respond to electromagnetic, e.g. infrared or visual wavelength, signals. These include both active devices, which can transmit signals, and passive devices, which only receive signals. Examples of active devices include radar sets and radio communication systems. Examples of passive devices include infrared detection systems and radio navigation receivers.

G. AVIONICS DISPLAYS

The cockpits of today's modern tactical aircraft and civil air transport aircraft are now host to numerous programmable displays and crew interface devices. The familiar analog, electro-mechanical gauges that were the standard for the 1950s through early 1970s aircraft cockpits have largely been replaced by systems incorporating either cathode ray tube (CRT) or liquid crystal display (LCD) technology. These video display devices provide the same sort of information to the pilot; heading, altitude, direction, speed, navigation cues, etc. The format of the display is in many cases similar or even identical to the electro-mechanical device that the CRT or LCD replaces. However, the video displays are not limited to emulating the older analog devices. They can be programmed to combine the information that formerly required two or more instruments to display into a single "picture" for the pilot. For the crew interface devices (e.g. multifunction display control panels) the new touchpads, keys and digital readouts have replaced the familiar knobs and dials of earlier aircraft cockpits.

These new digital displays and crew interface devices are based on the use of microprocessors for control of the video display. The cockpit instruments, especially the flight instruments, are generally considered to be critical systems. As a result, the certification of software as well as hardware has emerged as a significant design driver in digital avionics systems.

The flight critical CRT or LCD displays must: be assured of reliable, uninterrupted power; have software that is demonstrated to be reliable in use; and have hardware that meets or exceeds the reliability standards for the application. Thus, the possibility of damage to the display itself, the interconnecting wiring or data bus, the power supply and the source of information to be displayed must be considered when examining safety and survivability. The possibility of damage to the software, or of a hidden "bug" in the software, is also a concern. Damage to any one of these elements could cause failure of the cockpit display systems and contribute to loss of control of the aircraft.

III. SUSCEPTIBILITY EFFECTS

A. SUSCEPTIBILITY

Aircraft combat survivability is made up of two elements: susceptibility, the inability of the aircraft to avoid being damaged by the various elements of the man-made hostile environment; and vulnerability, the inability of the aircraft to withstand the damage caused by the man-made hostile environment [Ref. 3]. Since the susceptibility of an aircraft is influenced by the aircraft's design, tactics, equipment and weapons, the contributions of a digital avionics system should be measured by both direct and indirect contributions to susceptibility reduction. This chapter will explore those contributions of the digital data buses used in digital avionics systems to the susceptibility of an aircraft.

The choice of a digital avionics system will have an effect on the six major concepts for reducing susceptibility [Ref. 3]:

- Threat warning.
- Noise jamming and deceiving.
- Signature reduction.
- Expendables.
- Threat suppression.
- Tactics.

B. THREAT WARNING

The first of these susceptibility reduction concepts, threat warning, refers to aircraft systems that provide information on the location, type and status of the threat elements in the vicinity of the aircraft. Examples of threat warning systems include: radar warning receivers, laser warning receivers and missile approach warning systems.

These systems can be installed in an aircraft in a "stand alone" mode, with discrete wiring, controls and display(s) for each individual system. If a digital data bus design is used instead, the connectivity options that are available make it possible to replace many of the discrete portions of the system. For example, the data bus can be used to interconnect the antenna(s), processor, controls and displays of a threat warning system. A higher level of integration is also possible, where the control and display functions are shared with other systems. If the display processor is sufficiently capable, sensor fusion techniques, such as correlating radar returns with threat warning data, are possible. Another indirect benefit of the use of a data bus can be to allow for queuing of an expendables launcher, based on the threat warning system. Therefore, the contributions of a digital data bus to the susceptibility reduction factor of threat warning are due to the connectivity, shared control and shared displays, along with options for sensor fusion and queuing of expendables.

C. NOISE JAMMING AND DECEIVING

The second susceptibility reduction concept is noise jamming and deceiving, also called "jamming", "spoofing" or "defensive electronic countermeasures (DECM)". There are many

different techniques available, each of which exploits some weakness in the threat system.

As with threat warning, these active noise jamming and deceiving systems can be installed in an aircraft in a "stand alone" mode, with discrete wiring, controls and display(s) for each individual system. If a digital data bus design is used instead, the connectivity options that are available make it possible to replace many of the discrete portions of the system. Queuing of an expendables launcher in concert with the noise jamming and deceiving system is also possible. Therefore, the contributions of a digital data bus to the susceptibility reduction factor of noise jamming and deceiving are due to the connectivity, shared control and shared displays, along with the option for queuing of expendables.

D. SIGNATURE REDUCTION

The third susceptibility reduction concept is signature reduction, sometimes referred to as "stealth". Signature reduction typically encompasses the radar, infrared, noise and visual signatures. The digital data bus itself gives off virtually no electromagnetic or noise signature that is detectable outside the aircraft since it operates at very low voltages within either a shielded cable or a fiber optic cable.

However, a major consideration of radar signature reduction is to reduce the number and size of radar reflectors, of which antennas are a prime example. The use of a digital data bus, with its options for connectivity, can make possible the sharing of sensor apertures, thus reducing the number and/or size of the antennas and hence the radar signature.

E. EXPENDABLES

The fourth susceptibility reduction concept is the use of expendables, usually understood to include chaff, flares, active jammers and aerosols. Expendables are usually designed to counter radar, infrared and visually directed weapons.

As with threat warning, these expendables systems can be installed in an aircraft in a "stand alone" mode, with discrete wiring, controls and display(s) for each individual system. If a digital data bus design is used instead, the connectivity options that are available make it possible to replace many of the discrete portions of the system Queuing of an expendables launcher in concert with the noise jamming and deceiving system or in concert with the threat warning system is also possible.

F. THREAT SUPPRESSION

The fifth susceptibility reduction concept is threat suppression, generally understood as a means of either keeping the bad guys from shooting at you or destroying their ability to shoot back. Lethal threat suppression systems may be carried either on specialized aircraft (e.g. "Wild Weasel") or on one's own aircraft and include various means of delivering ordnance on target, such as anti-radiation missiles.

An emerging use of digital data bus systems is to provide for onboard programming of threat suppression weapons. Either onboard or off-board sensors can be used to provide queuing to the threat suppression system, which can then program the weapon to respond to the specific type and location of the threat. This capability extends the tactical utility of the threat suppression system.

G. TACTICS

The sixth and last susceptibility reduction concept is tactics. The integration of multiple sensors, using sensor fusion techniques, and the options for automatic queuing of expendables and threat suppression systems are contributing to the rapid evolution of new tactics. As an example, a recent article [Ref. 14] reported the use of off-board targeting (from an EA-6B) to provide threat information in support of the launching of a threat suppression weapon system (an F-16 carrying a HARM missile). The aircraft involved made use of digital data buses and a digital data link to transfer information among the various systems.

IV. VULNERABILITY EFFECTS

A. VULNERABILITY

Vulnerability is the inability of the aircraft to withstand the damage caused by the man-made hostile environment [Ref. 3]. Each of the components in the aircraft has a degree of vulnerability which contributes to the overall aircraft vulnerability. Components whose loss of function or kill mode would lead to the kill of the aircraft are referred to as critical components [Ref. 3: p. 137]. A kill mode refers to the reaction of the component or system when hit, such as a fire or explosion. Identification of these critical components and their kill modes is a key part of a vulnerability assessment.

B. KILL CATEGORIES

The discipline of aircraft combat survivability provides definitions for the aircraft kill categories, further divided into two sub-categories:

- Attrition, where the aircraft is lost to inventory. There are four levels of attrition:
  - KK= catastrophic (immediate loss of control)
  - K= loss of control within 30 seconds after a hit
  - A= loss of control within 5 minutes after a hit
  - B= loss of control within 30 minutes after a hit
- Mission Abort, where the aircraft returns to base, but does not complete the mission due to combat damage.

Because of the nature of electronics devices, combat damage is likely to result in either the immediate loss of function or

the component will survive. From an avionics perspective, the most likely causes of an attrition kill would be by damage to the flight control system in a "fly-by-wire" aircraft or to the primary flight display system in a "glass cockpit" aircraft. Most other damage to avionics is more likely to result in a mission abort kill [Ref. 15: P. 9].

C. DAMAGE MECHANISMS AND DAMAGE PROCESSES

A damage mechanism is the output of the warhead that causes damage to the target, sometimes referred to as a kill mechanism [Ref. 3: P. 84]. For an avionics system, the damage mechanisms of interest include:

- penetrators/fragments (from warheads or projectiles)
- blast, incendiary
- electro-magnetic pulse (EMP)

These damage mechanisms cause resultant damage processes, such as penetration and combustion, when they interact with the aircraft. Terminal effects refer to the ultimate response or effect of the damage mechanism on the aircraft components. These terminal effects can lead to a specific kill mode, which is defined as a damage-caused failure of a component [Ref. 3: p. 142]. Kill modes for avionics components may include:

- severing (a physical break in a wire)
- grounding (signal diverted to ground)
- corrupting (signal degradation due to damaged EM shield or EMP)
- loss of integrity (crushed, casing penetrated, etc.)
- overheating (resulting from fire or explosion)

The effect of these damage mechanisms on the survival of the aircraft varies depending on the criticality of the component(s) affected.

D. VULNERABILITY ASSESSMENT

A Vulnerability Assessment is the process of assigning numerical values for the various measures of vulnerability, i.e. vulnerable area [Ref 3: p.153]. The general requirements for conducting a vulnerability assessment are [Ref. 3]:

- Select a kill category and level
- Assemble the aircraft technical and functional description
- Determine the critical components and their kill modes for the selected kill category and level
- Select the threat
- Determine the critical component kill criteria
- Compute the vulnerability measure for the selected threat and kill category and level

The first task in a vulnerability assessment is to identify the critical components and their kill modes. Once the critical components and their kill modes have been identified, a vulnerability assessment can be conducted to quantify the measures of component and aircraft vulnerability, expressed in terms of vulnerable area to a specific threat.

The vulnerability assessment is typically presented in a graphical form, known as either a "kill tree" or "fault tree". An example is shown as Figure 6. This graphic presentation method is used by survivability engineers, with any break in a vertical line joining the critical components representing an

assumed result of an aircraft kill. This is a variation of survivability logic diagrams, which are related to reliability (logic) diagrams, where possible failure modes and outcomes are displayed in a logic diagram. In reliability engineering, damage due to hostile action is usually excluded from the discussion.

Vulnerability is expressed in relation to a specific man-made threat, such as 23mm High Explosive Incendiary (HEI) shells. For most aircraft, there will be areas where the aircraft can withstand a hit by a 23mm HEI, while in more critical areas, such a hit could damage a critical component, leading to loss of the aircraft. The vulnerable area (Av) is a theoretical area of the aircraft which is presented to the threat from a particular direction that, if hit in this area, would result in an aircraft kill [Ref.3: p.154]. The ratio of the aircraft's vulnerable area to its presented area represents the probability that the aircraft is killed given a random hit on the aircraft (Pk/h) [Ref. 3: p.154]. Once the vulnerabilities of the aircraft are understood, design features can be used to reduce vulnerability.

These vulnerability reduction features can have a cost and weight penalty. One of the major uses of the vulnerability assessment is to predict the probable reduction in aircraft losses in the event that the aircraft is equipped with specific survivability enhancement features. The cost of these features can then be related to the probable cost savings expressed in aircraft and aircrew not killed. This information can then be used to support a decision on whether to include a certain vulnerability reduction feature, or not, based on the anticipated benefits versus the probable costs.

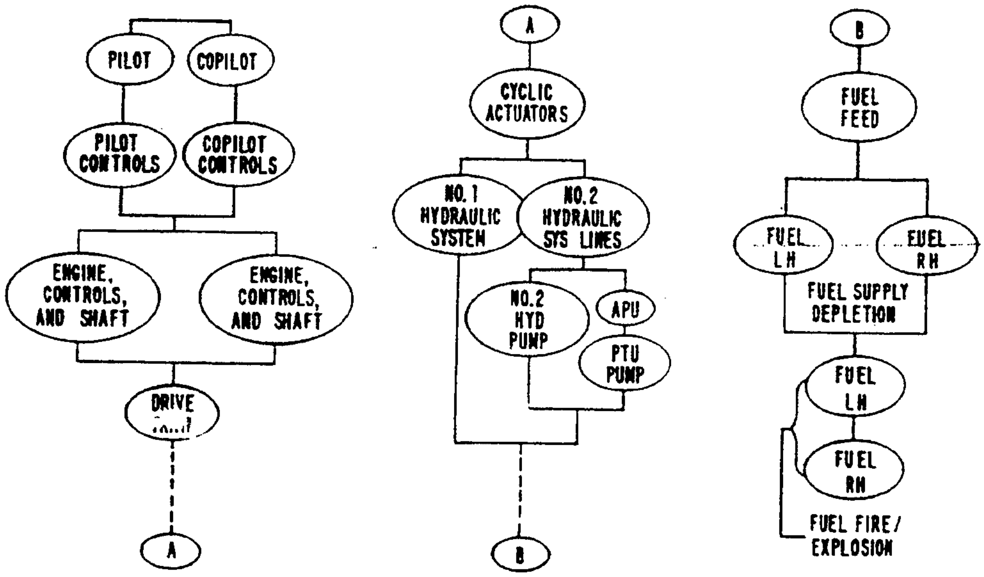

Figure 6, Example Kill Tree For a Two Engine, Two Pilot Helicopter, From Ref. 3

E. CRITICAL COMPONENTS

The general definition of a critical component is one whose loss leads to a loss of function or whose kill mode leads to an aircraft kill. Also considered are critical components whose loss of function or kill mode would lead to the kill of another critical component that provides an essential function. [Ref. 3]. Critical components may be either redundant or non-redundant.

For the purposes of this thesis, the focus will be on the critical components of the avionics system, especially the data buses. In general, a data bus consists of remote

terminals, couplers and a cable (wire or fiber optic). The data buses provide for the connectivity between the various avionics devices. These avionics devices exist as remote terminals on the data buses.

A remote terminal can be a critical component, depending on the function that the individual remote terminal performs. The remote terminal that functions as the bus controller is a critical component in any data bus that uses a bus controller protocol (such as MIL-STD-1553B) if the loss of this data bus will lead to a kill of the aircraft. The loss of the bus controller or its functions will result in the loss of all data bus functions, unless a back-up bus controller is available. This is because of the command/response design protocol which employs a bus controller to de-conflict the various remote terminals, preventing simultaneous transmissions over the data bus.

Data bus couplers and associated stubs leading to remote terminals are of different design for each of the three transmission modes: voltage-coupled, current-coupled and fiber-optic. The failure of a coupler located between the data bus cable and a remote terminal that is a critical component could result in the loss of an essential function performed by that component. The data bus couplers in a voltage-coupled data bus are designed to electrically isolate individual remote terminals from the data bus and are unlikely to directly cause a data bus failure (Figure 7). The data bus couplers used in a current coupled data bus are extremely unlikely to directly cause a data bus failure because they do not require any break in the data bus cable (Figure 8). The data bus couplers used in a fiber-optic data bus could cause a data bus failure if badly damaged. Since they are permanently fused to the cable and have no moving parts, damage to the coupler would be likely to simultaneously damage the cable by disrupting the light path. In all three cases, couplers are

critical components if the remote terminal that they serve is considered to be a critical component.

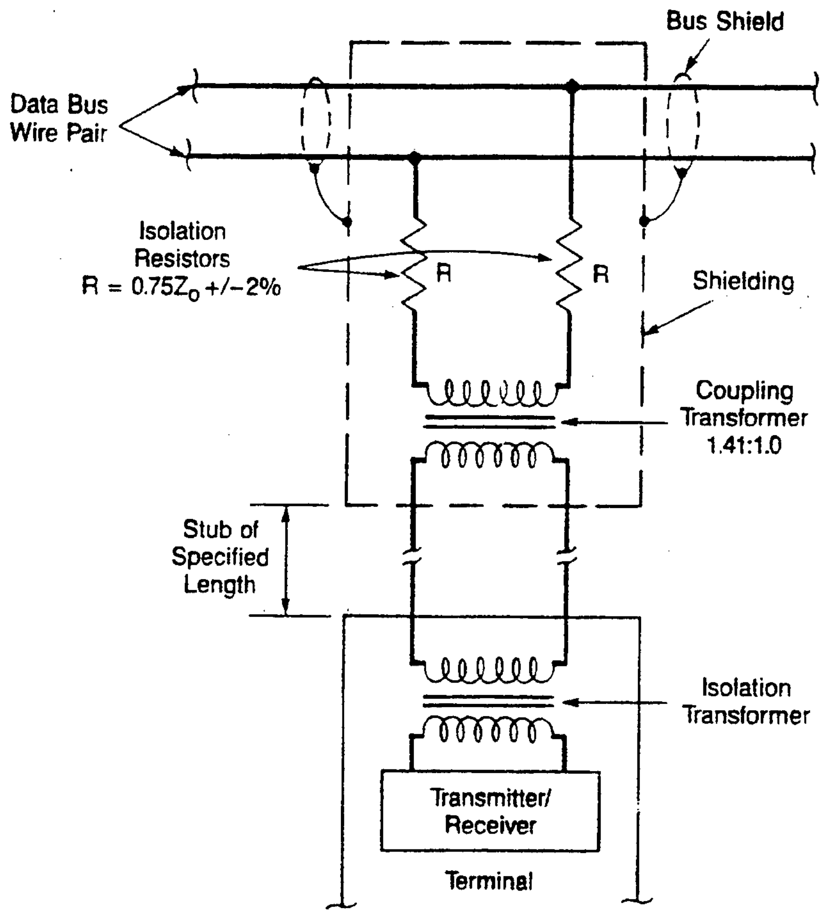

Figure 7, Data Bus Coupler, Voltage-Coupled (From Ref. 6)

The cable (wire or fiber-optic) that connects the various remote terminals is another critical component, if the loss of the data bus will lead to a kill of the aircraft. Severing of the wire or fiber-optic cable due to impact by a penetrator or by secondary means (e.g. fire, explosion) will generally result in loss of data bus function. Similarly, loss of cable shield integrity will be likely to disable the wire data bus if the signals are diverted to ground or are corrupted by electro-magnetic interference. A fiber-optic data bus can

continue to function with a damaged shield as long as the light-transmitting fiber is intact.

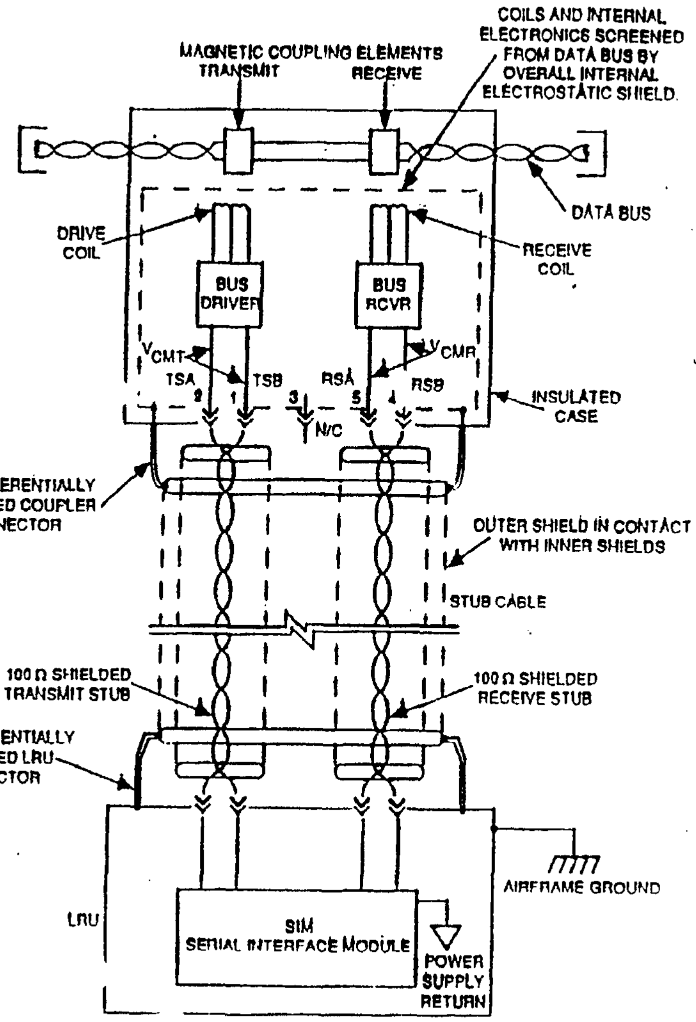

Figure 8, Data Bus Coupler, Current-Coupled (From Ref. 13)

F. LOSS OF FLIGHT CONTROL (ATTRITION) KILL

An aircraft with a "fly-by-wire" or "fly-by-light" flight control system depends upon data buses to provide a reliable data path for the flight control signals. To ensure adequate

reliability, three or four data buses operating in parallel are typically used. These data buses provide for communications between the flight control computer, inertial and air data sensors, flight control servos and other components of the flight control system.

The critical components of a "fly-by-wire" or "fly-by-light" flight control system include:

- flight control computers
- flight controls
- aircraft motion data sensors (INS, GPS, air data)
- lata buses
- flight control servos
- flight control power systems (hydraulic or electric)
- flight control surfaces

From the perspective of the avionics system, these flight control systems can be disabled by the following kill modes:

- disruption of the control signal path
- loss of aircraft motion data (for unstable aircraft)
- fire/explosion/overheating

An aircraft kill could result from damage to the control signal paths from the pilots' flight controls to the flight control computer(s); damage to the data buses from the flight control computer such that the signals cannot reach their intended destination; and damage to aircraft motion data sensors or their connection to the flight control computer(s). If the aircraft is an unstable aircraft, such damage will be likely to result in an attrition kill. In a stable aircraft, such damage may result in a mission abort kill, assuming that

there is a functional backup control system which provides the aircraft with a "get home" capability.

Figure 9 shows a sample "kill tree' that presents the critical components of a "fly-by-wire" flight control system in a graphical form [after Ref. 15]. The kill tree for the "fly-by-wire" flight control system shows the reduced vulnerability of the system that results from the use of multiple, redundant data buses for transmitting the flight control signals. However, there are possible single point failures for the flight control system at each of the flight control servo locations and at the flight control computer (which typically serves as the bus controller). This is because all of the data buses are in close proximity at these locations, since it is typical for all of the data buses to be used for pathways from the flight control computer to each of the flight control servos. A hit which disables the flight control computer(s), or a hit in the vicinity of the servos could conceivably disable all of the data buses simultaneously since cables and couplers are not hardened.

A hit that causes the failure of any of the critical components of an individual data bus (bus controller, cable and couplers to other critical components) could lead to failure of that individual data bus. Since only one of the other data buses has to survive in order to maintain system functionality, a minimum of one failure of a critical component in each of the data buses would be necessary to block the transmission of the flight control signals from the flight control computer to the servos.

Figure 10 shows a sample "kill tree' that presents the critical components of a "fly-by-wire" flight control system data bus in a graphical form [after Ref. 15].

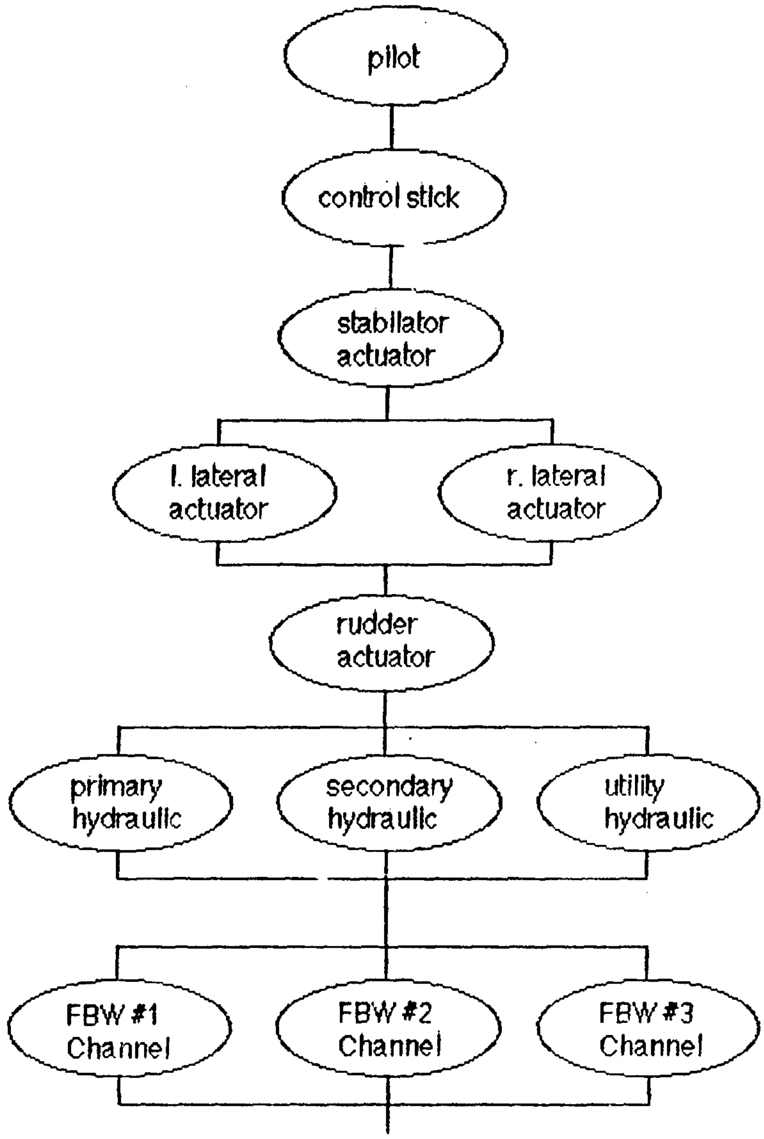

Figure 9, Flight Control (Attrition) Kill Tree

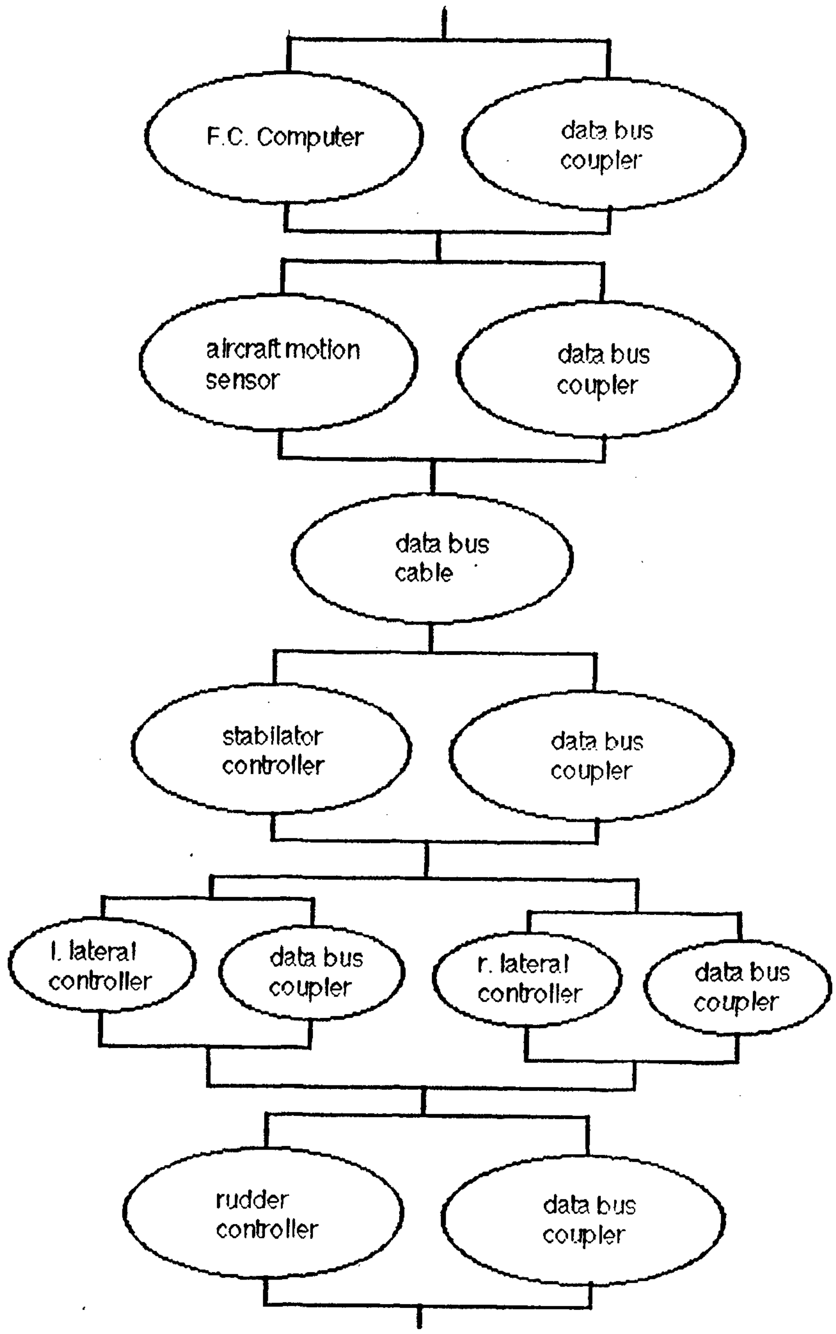

Figure 10, Flight Control Data Bus (Attrition) Kill Tree

G. LOSS OF ENGINE CONTROL SYSTEMS (MISSION ABORT) KILL

In general, combat damage to the engine electronic control systems will be unlikely to directly result in attrition, with a mission abort being a much more likely outcome. This is because of the stand-by or manual engine controls that are typically provided to give the pilot a "get home" capability. Loss of communications between the engine control systems and the air data reference systems due to damage to the data bus is one possible scenario that could lead to a mission abort. The critical components of an engine control system can include:

- data buses
- displays (e.g. CRTs or AMLCDs)
- display drivers
- flight reference systems (e.g. air data)
- throttles
- engine control computer(s)

From the perspective of the avionics system, these can be disabled by the following kill modes:

- penetrator/fragment damage leading to severing or grounding
- fire/explosion/overheating

The loss of an element or various elements of the engine control system may be considered sufficient to warrant a mission abort, depending on the nature of the mission.

The "kill tree" for the engine control system shows the reliance of the system on the data bus or data buses to share information and to manage the system. See Figure 11 for a

sample "kill tree' that presents these critical components in a graphical form.

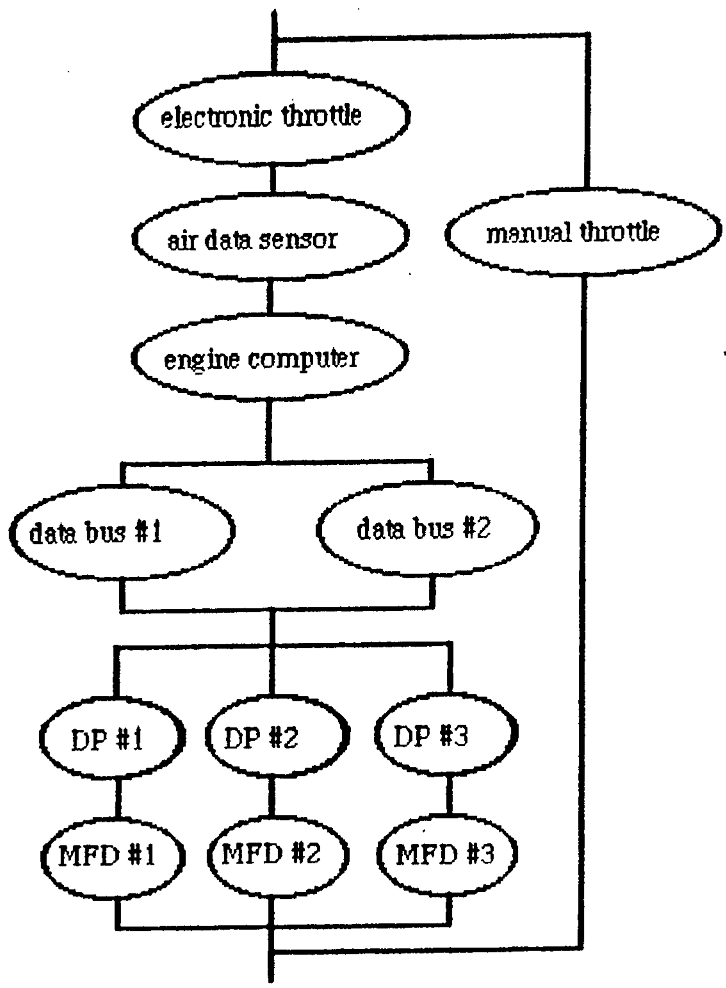

Figure 11, Engine Control System (Mission Abort) Kill Tree

H. LOSS OF FLIGHT AVIONICS (MISSION ABORT) KILL

In general, combat damage to the flight avionics is unlikely to directly result in attrition, with mission abort being a much more likely outcome. This is because of the stand-by or secondary flight instrumentation that is typically

provided (e.g. "peanut" gyro), even in a "glass cockpit" aircraft, to give the pilot a "get home" capability. Loss of communications between the "glass cockpit" displays and the flight reference systems due to damage to the data bus is one possible scenario that could lead to a mission abort. The critical components of a flight avionics system can include:

- data buses
- displays (e.g. CRTs or AMLCDs)
- display drivers
- flight reference systems (e.g. gyros, motion sensors)
- central computer(s)

From the perspective of the avionics system, these can be disabled by the following kill modes:

- penetrator/fragment damage leading to severing or grounding
- fire/explosion/overheating

The loss of an element or various elements of the flight display system may be considered sufficient to warrant a mission abort, depending on the nature of the mission and environmental conditions.

The "kill tree" for the flight avionics system shows the reliance of the system on the data bus or data buses to share information and to manage the system. See Figure 12 for a sample "kill tree' that presents these critical components in a graphical form.

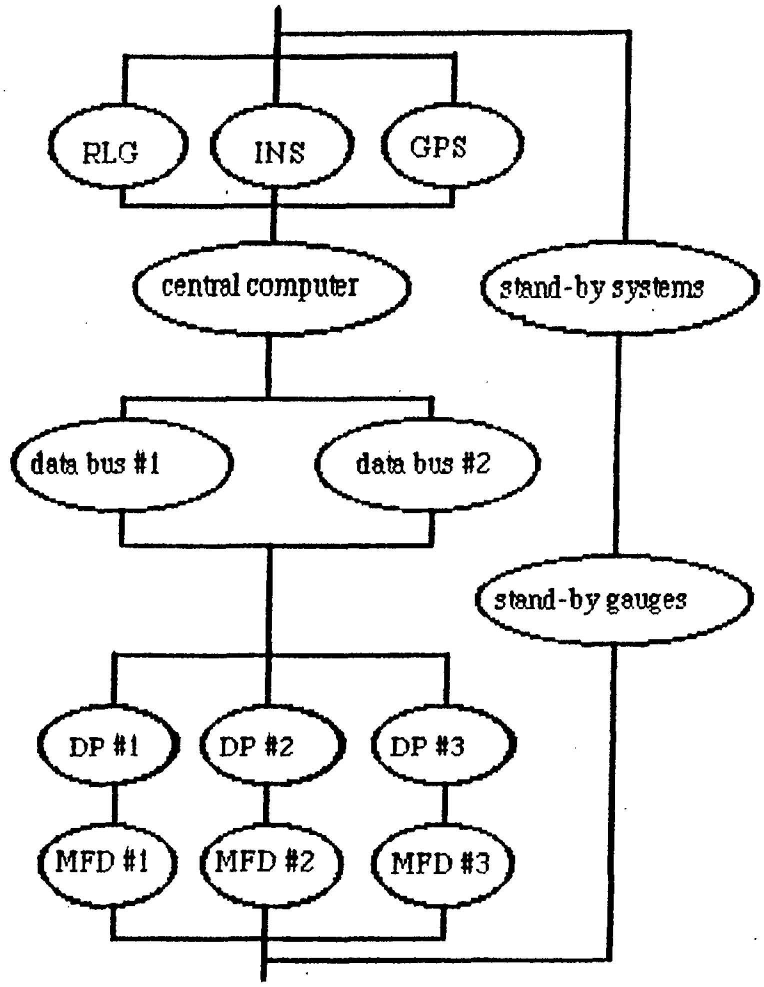

Figure 12, Flight Avionics (Mission Abort) Kill Tree

I. LOSS OF TACTICAL SENSOR SYSTEMS (MISSION ABORT) KILL

In general, combat damage to the tactical sensor systems is unlikely to directly result in attrition, with mission abort being a much more likely outcome. Loss of communications between sensors or between sensors and displays due to damage to the data bus is one possible scenario that could lead to a mission abort.

The critical components of a tactical sensor system can include:

- data buses
- displays
- threat warning & countermeasures systems
- central computer(s)
- sensors (radar, electro-optical, etc.)
- electronic warfare systems

From the perspective of the avionics system, these tactical sensor systems can be disabled by the following kill modes:

- penetrator/fragment damage leading to severing or grounding
- fire/explosion/overheating

The loss of an element or various elements of the tactical sensor system could be considered sufficient to warrant a mission abort, depending on the nature of the mission and magnitude of the expected threat.

The "kill tree" for the tactical sensor system shows the reliance of the system on the data bus or data buses to share information and to manage the system. Figure 13 shows a sample "kill tree' that presents these critical components in a graphical form. Whenever an avionics architecture that incorporates the tactical sensor systems via a data bus is used, there is a clear requirement for one or more backup data buses in order to ensure system integrity in the event of damage. Failure of any individual system (e.g. threat warning, countermeasures, radar, etc.) is unlikely to lead to a mission abort in all cases. However, failure of the entire data bus system or display system would most likely result in a mission abort. A crew may be able to continue the mission with a single sensor system disabled, but would be unlikely to

continue the mission with a complete failure of all tactical sensor systems.

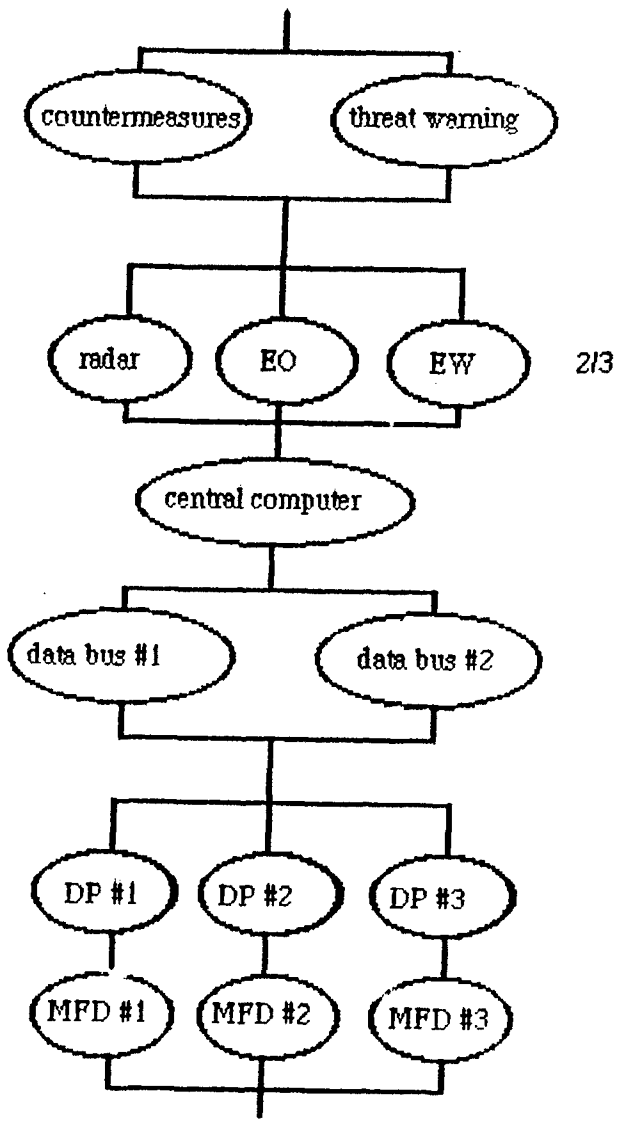

Figure 13, Tactical Sensor Systems (Mission Abort) Kill Tree

J. ARCHITECTURES

1. Federated

In a federated avionics system architecture, a moderate degree of control and coordination is handled by a central mission computer. The individual elements of the system usually have dedicated, independent data processors and are interconnected via data buses, typically via the MIL-STD-1553B. This degree of interconnectivity allows the system elements to work in cooperation and to share information, which is the major advantage of the federated syst m over the independent architecture. From a vulnerability standpoint, there are two weaknesses: 1) reliance on a central computer for control and coordination; and 2) reliance on shared data that is distributed via interconnecting data buses.

The key survivability issue for a federated system is to ensure uninterrupted and uncorrupted communications between the various avionics systems via the data bus or buses. Since the different systems are dependent upon a common data base, any break in this flow of data will cause system degradation. The exact nature of the degradation will be dependent upon the individual system function and the criticality of the data.

A critical component for a federated architecture is the central computer that functions to coordinate and control the various system elements. Unless a backup computer is available, this can represent a single point kill for the avionics system. With the central computer's functionality disabled, the interconnected systems may be unable to function independently.

Similarly, the data buses used to connect the system elements to the central computer are critical components. Disabling all of these data buses will serve to isolate the

central computer and each individual system element from the rest of the system. This will prevent the essential flow of shared data and control signals, which is likely to result in the loss of much, if not all, of the functionality of the federated system. Figure 14 shows the critical components of the federated avionics architecture.

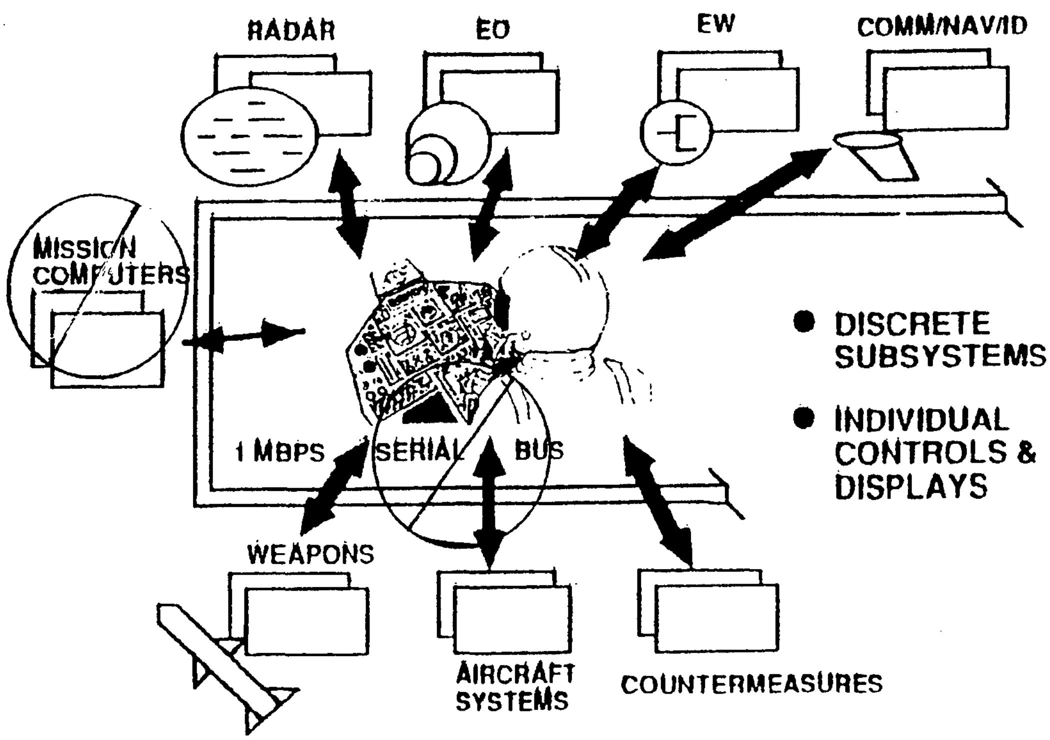

Figure 14, Federated Architecture Critical Components, After Ref. 1

2. Centralized

In a centralized avionics architecture, the main elements of the avionics system are packaged in standard modules which are located in one or more densely packed avionics racks. The system elements within the avionics racks are interconnected by means of high speed backplane buses, while connections to

the various sensors and displays are made via both conventional and high speed data buses. Because the computer processing capabilities of the integrated architecture are centrally located and are shared among various elements, the data buses must be capable of handling a very high data rate. The centralized architecture makes extensive use of common modules and the sharing of the computer processors. To an even greater extent that the federated architecture, the survivability weaknesses of the centralized architecture are: 1) nearly total reliance on a central processor for data processing, control and coordination; 2) close proximity of critical components in a common avionics rack; and 3) reliance on data that is distributed via interconnecting data buses.

This architecture may have two major disadvantages in a combat environment: 1) it depends on many long data buses to collect and disseminate both data and command signals and 2) the loss of the single or co-located central computer(s) could result from a single hit. Since the other elements of a centralized system are largely dependent upon the central processing unit(s) for inputs, direction and coordination, loss of the central computer(s), or loss of communication with the central computer(s), could significantly degrade mission performance even to the extent of causing a kill of the aircraft.

A critical component for an centralized architecture is the central avionics rack that contains the processing modules which function to process data, coordinate and control the various system elements. Since the design co-locates the backup processors in the same or an adjacent avionics rack, this can represent a single point kill for the avionics system. With the centralized processing disabled, the centralized system may be unable to function unless some backup processing capability is provided in another location.

Similarly, the data buses used to connect the system elements to the central processors are critical components. Disabling these data buses will serve to isolate the central processors from the individual system elements. This will prevent the essential flow of data from the sensors to the processors and from the processors to the displays. Without a reliable data path, the functionality of the integrated system is likely to be compromised. Figure 15 shows the critical components of the centralized architecture.

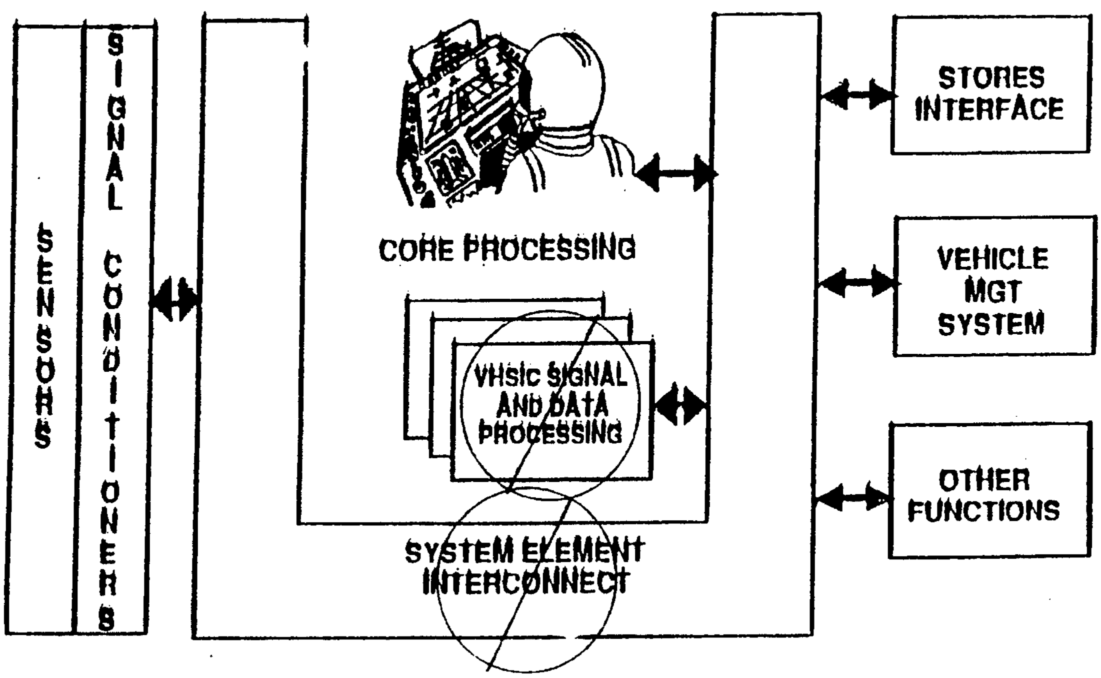

Figure 15, Centralized Architecture Critical Components, After Ref. 1

3. Distributed

The distributed architecture is similar to the integrated architecture in the use of common modules located in racks or cabinets. It different in that a significant amount of data

processing is accomplished at the subsystem or element level. Rather than being located at a single, central location, the processors are distributed throughout the aircraft in nodes. A processor-intensive element, such as a radar or electronic warfare system, will typically incorporate a significant preprocessing capability at or near the antenna location. These processor nodes are interconnected via data buses, but are capable of some independent operation.

This architecture may enjoy several advantages in a combat environment, including: 1) less reliance on data buses; 2) intrinsic partitioning and 3) residual capability should communication with other system elements be interrupted [Ref. 1: p. 6].

Critical components for a integrated architecture are the avionics racks that contain the processing modules which function to process data, coordinate and control the various system elements. Since the design distributes these modules in nodes throughout the aircraft, a significant survivability advantage, there may be no single point kill for the avionics system, especially if the system can be dynamically reconfigured. With one or more of the processing nodes disabled, the distributed system may be able to continue to function, unless some essential capability is lost.

Similarly, the data buses used to interconnect the processor nodes located at the various system elements are critical components. Disabling these data buses will serve to isolate the distributed processors from the each other and their individual system elements. This will prevent the essential flow of data from the sensors to the processors and from the processors to the displays. Without a reliable data path, the functionality of the distributed system is likely to be compromised. In a similar manner as with the centralized architecture, redundant, physically separated data buses can be used in order to ensure a reliable data path for the

system. Figure 16 shows the critical components for a distributed architecture.

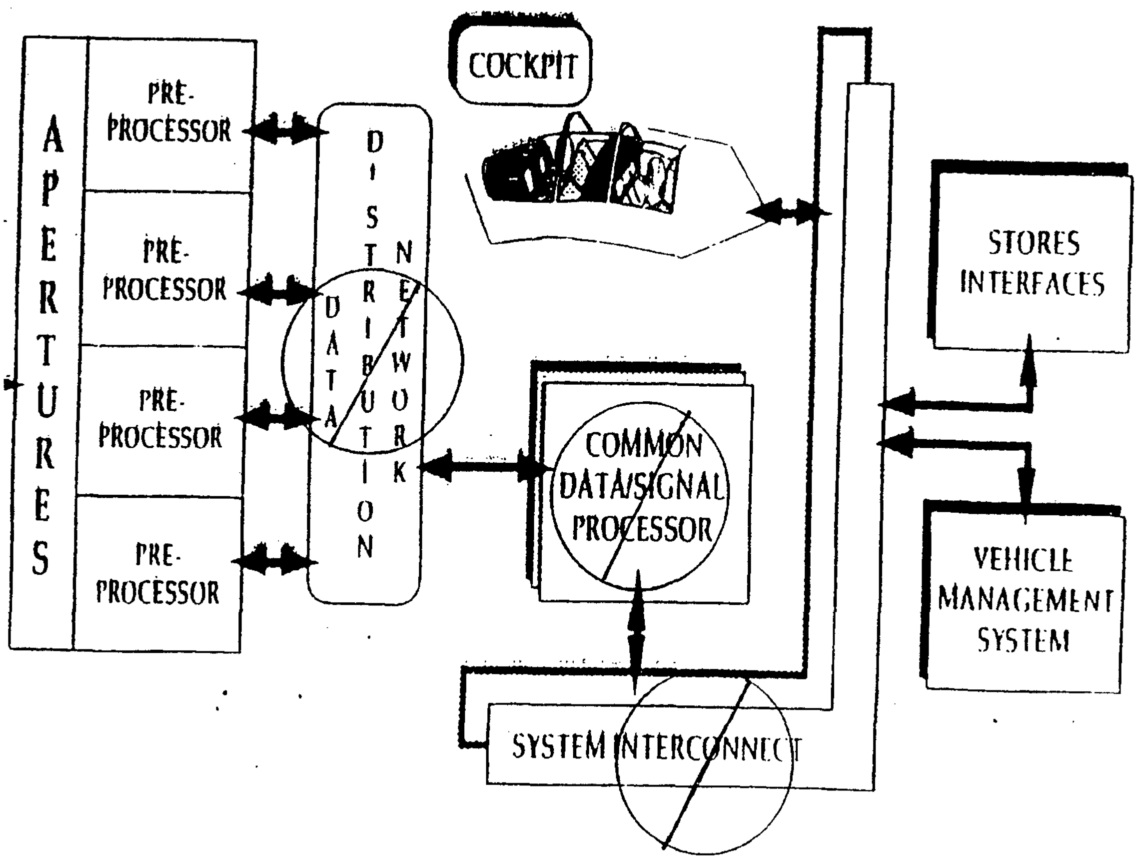

Figure 16, Distributed Architecture Critical Components, After Ref. 1

V. COMPUTING THE VULNERABLE AREA OF AVIONICS COMPONENTS

A. VULNERABILITY ASSESSMENT

As a part of the vulnerability assessment (VA) of the aircraft, it is necessary to:

- Select a kill category and level
- Assemble the aircraft technical and functional description
- Determine the critical components and their kill modes for the selected kill category and level
- Select the threat
- Determine the critical component kill criteria
- Compute the vulnerability measure for the selected threat and kill category and level

For the flight control systems, it is possible to conduct a VA assuming either an attrition or a mission abort kill. For the other systems, it is more probable that a mission abort kill will be appropriate for the VA.

The technical and functional descriptions are needed in order to identify the aircraft's critical components and to build a physical model of the component locations. Typically, a computer model of the aircraft that shows component locations is built using a computer aided design (CAD) software package. This model is then used to help determine the presented areas (Ap) of the components. In combination with the probability of killing a component given a hit on the component (Pk/h), the vulnerable area (Av) of a component can be determined [Ref. 3: p.158].

The vulnerable area of a given component is defined as the product of the presented area (Ap) in the plane normal to

the approaching damage mechanism and the probability of kill of the component, given a hit on the component (Pk/h). In equation form: Av = (Ap)(Pk/h) [Ref. 3: p. 159]. Since it is extremely time consuming to compute the aircraft vulnerability manually, a number of computer programs have been developed for this task.

Two types of computer programs, shotline generators and vulnerable area routines, are typically used sequentially to conduct a vulnerability assessment of an aircraft to a single hit by a penetrator or fragment [Ref. 3: p.192]. The shotline generator programs usually model the exterior surface of the aircraft and its components with either surface patches or various geometric shapes. The program then superimposes a planar grid over the aircraft's surface from a particular direction and passes a set of parallel rays or shotlines through the aircraft, one shotline being randomly located in each grid cell. The shotlines are always normal to the grid plane and from the direction of the threat mechanism. The program traces the path of each shotline through the aircraft and specifies which components have been encountered along the shotline.

The vulnerable area routines, of which COVART is currently the state-of-the-art, are used to generate component and total aircraft vulnerable area tables for a single penetrator or fragment [Ref 3: p. 194]. The means by which this is accomplished is described as follows:

> "The component vulnerable area of each grid cell is the product of the cell presented area and the probability of component kill for the shotline in that cell. The vulnerable area of each component is the sum of the component vulnerable areas computed for each grid cell whose shotline passes through the component. The total aircraft vulnerable area is the sum of all the cell vulnerable areas, considering only the nonredundant critical components and any redundant critical component overlap." [Ref 3: p. 195]

Once the individual aircraft components' probability of kill given a hit, (Pk/h) and presented area (Ap) have been determined, the computer methods described can be used to estimate the overall vulnerability of the aircraft to a given threat. Because of their small size, avionics devices make a relatively minor contribution to the overall vulnerable area of a typical aircraft. Large vulnerable components such as fuel tanks, engines and the cockpit usually have a much greater vulnerable area to a given threat than the avionics system. However, although avionics devices are small, they are frequently critical components whose loss or damage could result in an attrition or mission abort kill. A kill in most avionics components will not usually result in an aircraft kill, but may lead to a mission abort. The decision on whether or not to abort must take into account the specific mission, threat and environmental conditions, since different missions have different levels of reliance on the avionics system [Ref. 16: p. 9].

There are two classes of critical components that generally make up the avionics system, the "black boxes" (more formally known as Line Replaceable Units or LRUs) and the wires or cables that interconnect them. Because of the nature of electronics devices, the impact of a projectile or fragments will usually either produce an immediate kill of the component (LRU, wire or cable) or the unit will survive [Ref. 16].

B. "BLACK BOX" VULNERABILITY

The design of a typical avionics "black box", or LRU, is specified in applicable civil or military standards. These standards establish the form factor, external design, mounting and environmental operating conditions for avionics components

that are located in the avionics bay of an aircraft [Ref. 6: p.139]. Current standards include ARINC Specification 600 [Ref. 17], DOD-STD-1788 [Ref. 18] and MIL-M-28787 [Ref. 19]. Figure 6 shows the outline drawing of a DOD-STD-1788 LRU.

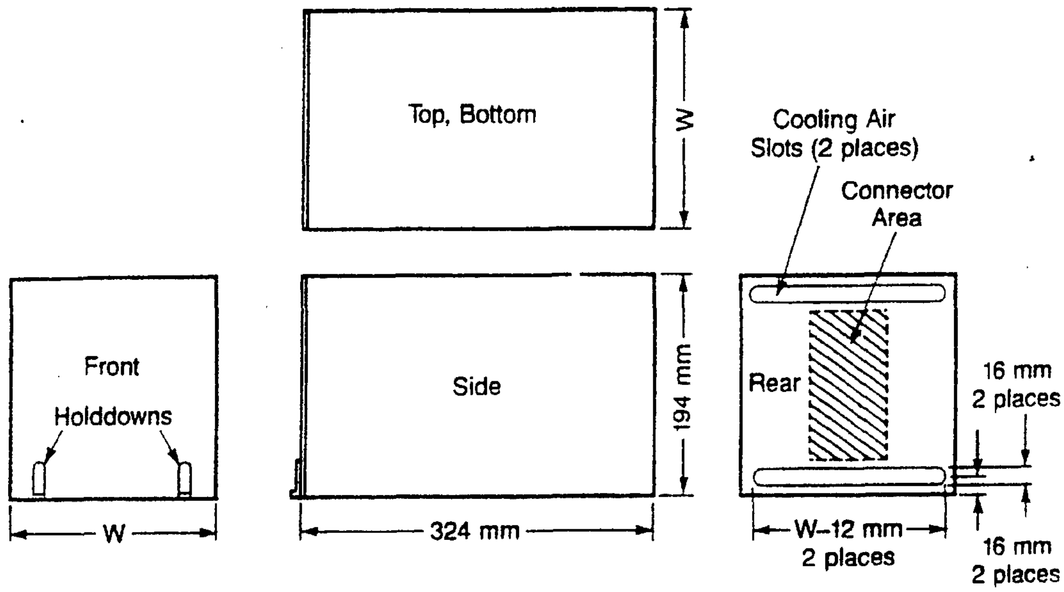

Figure 17, DOD-STD-1788 LRU (from Ref. 6)

The aircraft environment is typically described in precise, quantitative terms for the use of the avionics designer [Ref 6: p. 148]. The specified environment usually includes power, cooling and ambient air, pressure, temperature, vibration, shock, and the electromagnetic environment. This generally assumes a benign operating environment and does not typically specify the possible damage mechanisms that may be encountered by a tactical aircraft in a combat environment. The survivability requirements, such as ballistic tolerance to a given threat mechanism (e.g. 7.62 or

12.7 mm projectiles) is usually included in the overall aircraft specification since survivability is applicable to all systems, not just avionics.

For a given avionics component (LRU) to cease to perform its intended function as the result of a hit, the outer case must generally be penetrated by the damage mechanism (projectile or penetrator). This hole in the outer casing destroys the electromagnetic shielding and may compromise the forced air cooling system. Since LRUs are typically fairly densely packed with circuit cards and power supplies, the penetration into the interior of the LRU will cause a great deal of damage to these fragile assemblies. Internal health monitoring routines, such as built-in-test, are likely to identify the failure of multiple assemblies within the LRU as a result of the projectile or fragment damage. This will be likely to lead to a self-commanded shutdown of the component, unless this function is itself damaged. It is also possible that an electrical fault of sufficient magnitude to cause a fuse or circuit breaker to function will occur as a result of the hit, thereby cutting off power to the LRU. The kill of an electronics component after a hit by a projectile or fragment is likely to be immediate (less than one second) [Ref. 16: p. 10].

In the case of an explosive warhead, such as a 23mm HEI round, the effects on the LRU are devastating. Internal circuit card assemblies are temperature sensitive and the heat of the explosion is very likely to destroy the items located in the interior of the LRU. The probability of kill for such a warhead is likely to approach unity.

C. CABLE VULNERABILITY

Since avionics components are typically connected via cables or wires, the vulnerability of these cables and wires to damage by projectiles and fragments is a significant concern. Recent testing under the sponsorship of the Air Force [Ref: 20] has provided a great deal of information about the effects of projectile and fragment damage on wire bundles and cables. A major reason for concern about these effects is that damage to cables and wire bundles is difficult to locate and repair. While circuit breakers and fuses can be expected to protect the various avionics components, shorting to ground and arcing can be expected to result from the impact of a damage mechanism (projectile or fragment) on the wires or cable [Ref 20: p. 1]. In addition to disabling the power, control or signal path, the current carried by the severed cable presents a possible source of ignition for secondary fires or explosions.

When computing the vulnerable area of the aircraft, the contributions of the cables and wire bundles must be included since the loss of power or signals to a critical component is essentially equivalent to the loss of the component itself. While small in diameter, many wire bundles and cables have a large presented area because of their length. Most shotline generator computer programs conclude that a cable or wire is damaged by a projectile or fragment only if the centerline of the projectile or fragment passes through the cable or wire. This can lead to an underestimation of the vulnerable area, since penetration of the outer shielding that exposes the conductors is sufficient to cause damage and in many cases it is not necessary to completely sever the cable or wire to have damage occur. This effect is shown in Figure 18. Flint

[Ref. 20] proposes that a radius addition be added to all wire bundles and cables in order to compensate for the shotline methodology currently in use. This would increase the probability of a hit being recorded on a given cable or wire bundle and would correct for the currently understated number of hits that results from the shotline methodology in use. This should result in an increased presented area and a corresponding increase in vulnerable area a result of the contribution of the cables and wire bundles to the avionics system vulnerable area.

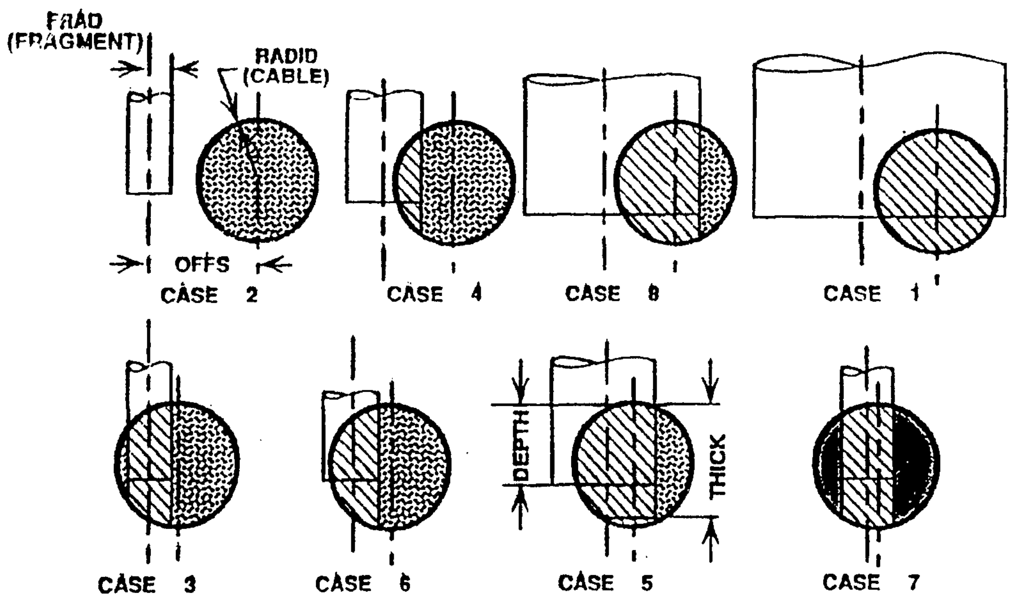

Figure 18. Effects of Fragment Size and Offset (from Ref.20)

VI. VULNERABILITY REDUCTION IN AVIONICS DESIGN

Digital avionics systems can contribute positively to the survivability of a tactical aircraft in many ways, including reducing the susceptibility of the aircraft (making the aircraft harder to hit) and reducing the vulnerability of the aircraft (making it harder to kill, if hit). Susceptibility factors were covered in Chapter III. Chapter IV discussed vulnerability effects for the most common types of avionics systems, with the exception of computer systems. Since the computer systems are of critical importance to all of the other avionics systems (e.g flight control systems, engine control systems, flight avionics systems and tactical sensor systems), the computer systems were not treated separately. The following chapter presents the six vulnerability reduction concepts as applicable to avionics systems.

A. VULNERABILITY REDUCTION CONCEPTS

Vulnerability reduction is defined as the use of any design technique or equipment to control or reduce the amount of damage or the consequences of damage to the aircraft, when the aircraft is hit by one or more damage mechanisms [Ref. 3]. The six vulnerability reduction concepts are [Ref. 3]:

- Component Redundancy (with separation)
- Component Location
- Passive Damage Suppression
- Active Damage Suppression
- Component Shielding
- Component Elimination

Each of these vulnerability reduction concepts may used to improve the survivability of the avionics systems.

1. Component Redundancy (With Separation)

Component redundancy refers to the use of multiple devices, parts or mechanisms to perform a given task [Ref 3]. Systems may be designed with total redundancy or only partial redundancy. A choice also exists between actual redundancy, using identical devices, parts or mechanisms, or functional redundancy only. The use of multiple, redundant data buses in parallel is an example of actual redundancy using identical components. The requirement for physical separation of the redundant devices, parts or mechanisms is intended to prevent the redundant items from being killed by a single event. For example, it would be considered good design practice to route the multiple redundant data buses as far apart from one another as possible, within the constraints of the aircraft structure. When the data buses are routed on opposite sides, damage to one side of the aircraft alone would be unlikely to result in loss of all data bus functionality.

2. Component Location

Component location means the choice in the design phase to position a component such that a damage mechanism is less likely to kill the component [Ref. 3]. Good design techniques applicable to improved survivability of avionics devices include:

- Orienting a component's presented area to reduce the likelihood of being hit by a damage mechanism coming from the most probable direction.
- Locating noncritical or ballistically hardened components in front of more vulnerable components.

- Reducing the presented area of non-redundant components.
- Locating components in order to prevent cascading damage.

In the case of a ground attack aircraft tasked with close air support, it would be good design practice to avoid locating critical components near the bottom of the aircraft, since this is the direction where the majority of damage mechanisms are likely to be coming from. For aircraft that use a central avionics bay, the demands for easy access for maintenance must be traded off with the need for survivability in locating the critical avionics components. For most aircraft, 'he trend towards component miniaturization aids aircraft survivability by reducing the presented area of critical components, thereby reducing the aircraft's vulnerable area.

3. Passive Damage Suppression

Passive damage suppression refers to features that either contain the damage or reduce the effects of the damage when an aircraft encounters a damage mechanism [Ref. 3]. Good design techniques applicable to improved survivability of avionics devices include:

- Damage Tolerance
- Ballistic Resistance
- Delayed Failure
- Fire and Explosion Suppression
- Fail-Safe Response

Most avionics components are composed of printed circuit cards and their associated power supply and backplane, located in a housing ("black box") that functions as an environmental

shield from dust, water, and electromagnetic interference and provides a channel for cooling air. The "black box" is typically optimized for light weight and small size, with ballistic resistance rarely being a consideration. Vulnerability reduction techniques available to the avionics designer include the use of materials that are tolerant of the loss of the integrity of the environmental shield that is the component housing. The key passive damage suppression technique for avionics is to ensure that components are able to be easily isolated via circuit breakers, preventing a "cascade" failure to the system.

4. Active Damage Suppression

Active damage suppression is a technique that employs a sensor or other device to sense the onset of a damage process and activates some mechanism that contains the damage or reduces its effects [Ref.3]. The chief example of this type of technique is a fire detection and extinguishing system. Since avionics devices are generally very sensitive to damage by fire or overheating, the use of fire suppression devices in avionics bays could improve their survivability.

5. Component Shielding

Component shielding refers to the technique of using coatings or materials that resist or absorb the damage mechanisms [Ref. 3]. The use of armor is the most common example of this technique. Here the design tradeoff is between the weight of the shielding and the necessary level of ballistic tolerance. Since most avionics devices are not themselves in hardened housings, this technique is usually applicable to shielding around the avionics bay. To save weight, the shielding is usually installed in only the most probable direction for the given damage mechanism.

6. Component Elimination

Component elimination refers to the design choice of either eliminating a component entirely or replacing it with another, less vulnerable, component [Ref. 3]. An example for an avionics component would be to choose a passively cooled component over one which relies on forced air cooling, since this reduces the component's vulnerability to damage should cooling air supplies be lost.

B. CHOICE OF AVIONICS ARCHITECTURE

The avionics designer has a choice of three main avionics architectures: federated, centralized and distributed. Each is highly dependent upon the uninterrupted flow of data via the digital data buses and on computer processing capability. The vulnerability reduction concepts applicable to each architecture are discussed below.

1. Federated

The federated system can be designed to be more survivable by providing physically separated backup data paths using multiple redundant data buses with backup bus controllers and a backup central computer. The use of multiple, interconnected data buses, each of which is dedicated to a particular function, can provide a degree of compartmentalization. The physical placement of the data bus cables should be as widely separated as possible, within the constraints of the aircraft design. The goal is to assure the reliable transmission of data between the various remote terminals in the system in order to maintain system integrity and functionality.

2. Centralized

The centralized system can be designed to be more survivable by providing backup data paths using multiple redundant data buses, either with backup bus controllers or by using newer data bus designs that do not rely on bus controllers. The physical placement of the data bus cables should be as widely separated as possible, within the constraints of the aircraft design, but all must converge at the central avionics rack(s). The use of a centralized, integrated processing capability means that it is nearly impossible to duplicate this capability in a physically separate location. Hence, the central processing and data distribution systems must be protected from damage in order to ensure survivability of the system. Hardening and/or shielding of the co-located group of critical components is the most likely vulnerability reduction concept to be effective without compromising the economic advantages of the centralized architecture.

3. Distributed

From a survivability perspective, it can be argued that the distributed architecture is preferable because damage at any single site should be unable to disable all systems. The remaining processing capability may be sufficient to enable a degree of system functionality even after some damage has been inflicted. Still, the information that is shared over the data buses could be interrupted due to damage, even if individual systems are capable of functioning. The impact of interrupting the data flow would be likely to impede continued system operation, making the availability of redundant data paths an essential consideration for a distributed architecture, just as it is for the federated and centralized architectures.

VII. CONCLUSIONS

In the design of a modern tactical aircraft, which is highly dependent upon digital avionics systems for its mission performance, attention should be paid to the survivability of the avionics systems when the aircraft is operated in a man-made hostile environment. The traditional considerations of reliability, fault tolerance and component redundancy that take into account known or anticipated failure modes of the avionics systems should be augmented by consideration of the catastrophic effects of combat damage.

For most common combat threats, damage to the avionics system is more likely to result in a mission abort kill than an attrition (loss of aircraft) kill. However, an unstable fly-by-wire aircraft could be attrited if the damage is sufficient to disable the flight control system. There may be an interesting parallel in the design of some fly-by-wire systems to the hydraulic system design that was typically used in the 1960s. At that time, all of the hydraulic systems were generally routed to each of the servo actuators. In combat, this proved to be undesirable in that a single massive hit to the servo area could knock out all of the aircraft hydraulic systems simultaneously. In some fly-by-wire designs, all of the data buses used to send flight control commands to the servos are likewise connected to each servo. It is possible that a single massive hit to the servo area could sever all of the data bus cables and disable all of the flight control data streams simultaneously, resulting in loss of control. Another possible single point failure is the flight control computer in an unstable aircraft. In some aircraft designs, the central flight control computer has such a major role in the flight control system that a disabling hit to this component will result in the loss of control, regardless of pilot input.

The majority of possible kill modes of avionics components will lead to a mission abort kill. The decision on

whether or not to abort must take into account the specific mission, threat and environmental conditions, since different missions have different levels of reliance on the avionics system. As modern tactical aircraft become increasingly reliant on their avionics systems, the contribution of these systems to the vulnerability of the aircraft is likely to increase.

It is probable that as more combat data is available, the survivability effects of digital avionics systems will be better understood. For now, the fact that avionics systems represent 30-40 percent of the aircraft fly-away costs, although only 5-6 percent by weight, dictates that a cautious approach to the effects of digital avionics systems on the survivability of modern tactical aircraft be pursued.

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Designing Digital Avionics Systems for Reduced Vulnerability

Wade D. Duym
Battelle Memorial Institute

Presented at:
Enhancing Aircraft Survivability
A Vulnerability Perspective
Monterey, CA
October 22, 1997

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This Presentation Is Based on a M.S. Thesis Written by the Author,

"Effects of Digital Avionics Systems on the Survivability of Modern Tactical Aircraft",

at the Naval Postgraduate School (NPS) Under the Direction of Distinguished Professor Robert E. Ball, Ph.D.

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Why Reduce Avionics Vulnerability?

Three Reasons:

- To Enhance Flight Safety
- To Anticipate and Counter Possible Terrorist Threats
- To Reduce or Minimize Damage Due to Military Threats

Why Worry About Digital Avionics Systems?

- Modern Aircraft Designs Incorporate Digital Avionics Systems
- Example Systems:
  - Fly-by-wire Flight Control Systems
  - Communications Navigation and Surveillance (CNS) Systems
  - Digital Engine Controls (FADEC)
  - Electronic Flight Information Systems (EFIS)
  - Digital Data Bus Systems
  -
- Example Aircraft:
  - Boeing 777, Airbus A340, etc.
  - F-22, JSF, etc.

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Digital Avionics Systems

- Consist of:
  - "Black Boxes"
  - Wires/Cables
-
- Depend on:
  - Supply of Electrical Power
  - Component Integrity
  - Tolerable Environmental Conditions

How Can Digital Avionics Be Damaged/Disabled?

- Loss of Electrical Power
- Fire/Explosive Effects
- Electromagnetic Interference (EMI)
- Electromagnetic Pulse (EMP)

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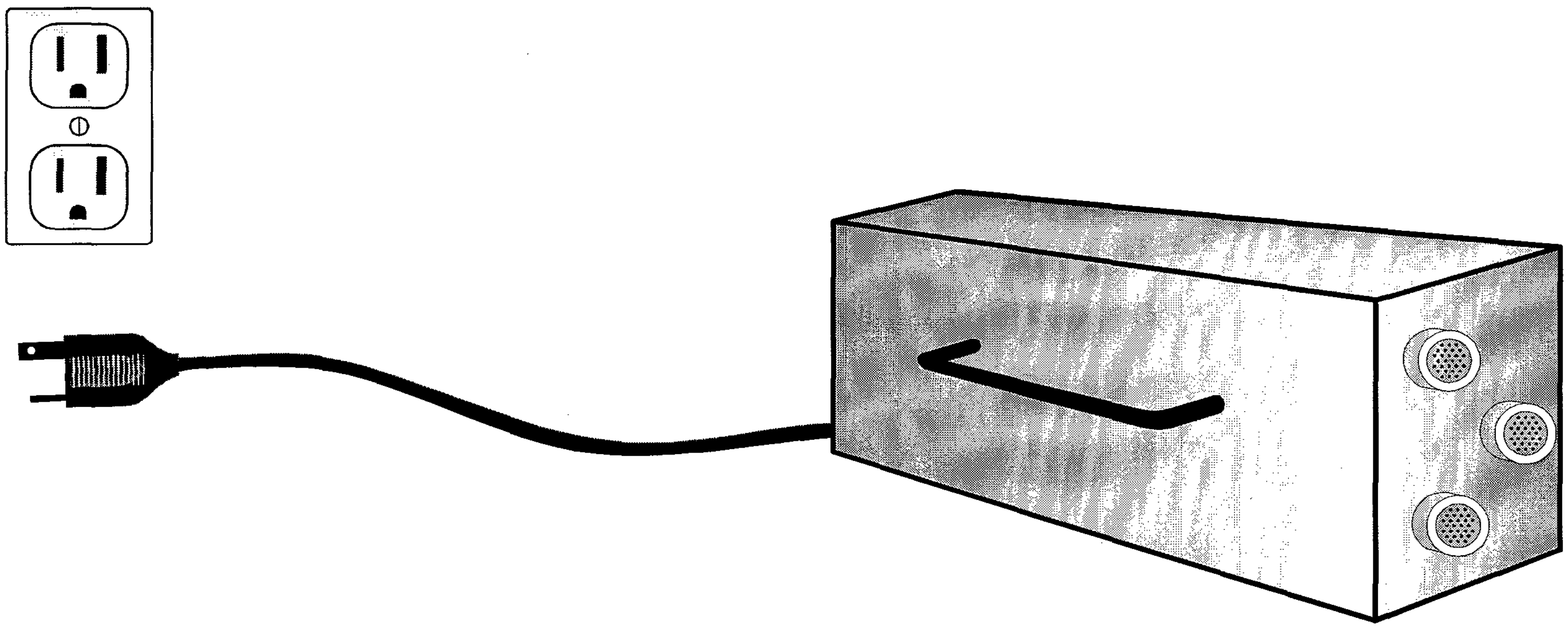
Loss of Electrical Power

Digital Avionics Need Reliable, Uninterrupted Electrical Power



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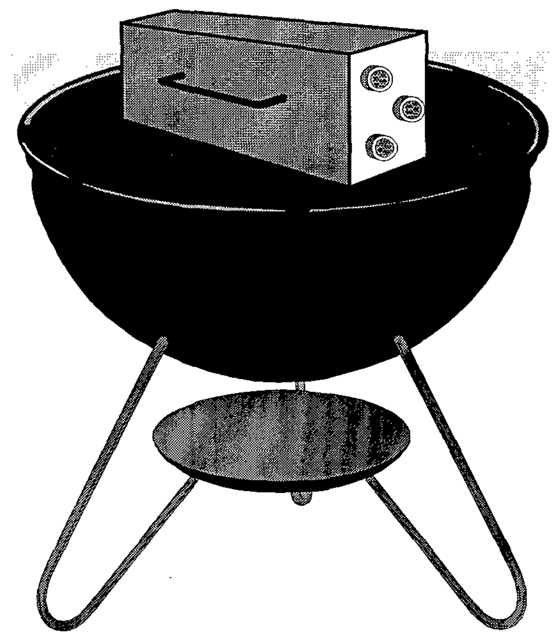
Fire/Explosive Effects

If Aircraft Structural Integrity is Lost
Avionics Are No Longer a Concern

•

If Aircraft Structural Integrity is Retained
Avionics are Needed



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Electromagnetic Interference/Pulse (EMI/EMP)

EMI/EMP Threats:

- High Intensity Radiated Fields (HIRF)
- Passenger Electronic Devices (PED)
- Terrorist/Military Use of Electromagnetic Devices

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Is There An EMI Threat?

Excerpt From a Major Airline's In-flight Magazine:

> **Electronic Equipment**: Certain electronic devices - such as AM and FM transmitters and receivers, portable telephones, televisions, video cameras and remote controlled toys - **may interfere with communications and navigation systems on the airplane**.

If Inadvertent EMI is Possible, How Difficult is it to Deliberately Cause EMI?

How Could We Screen Out Such Devices, or Detect Their Use?

Will Future Military Systems Exploit EMI/EMP?

Vulnerability Reduction Techniques Applicable to Avionics

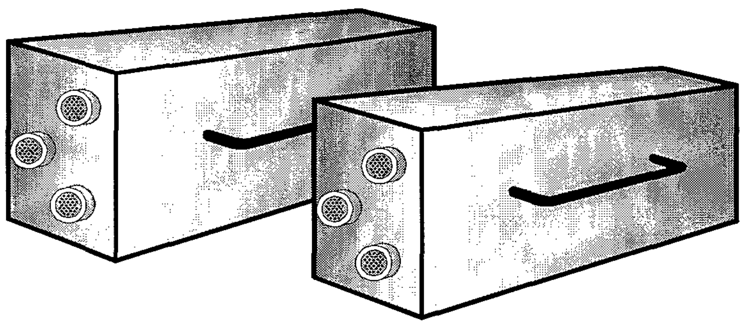
- Component Redundancy (with separation)
- Component Location
- Passive Damage Suppression
- Active Damage Suppression
- Component Shielding
- Component Elimination

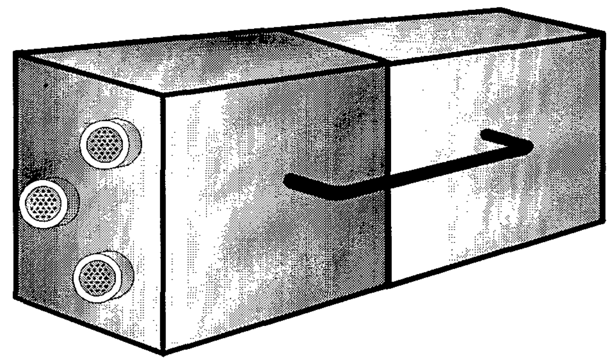
Component Redundancy With Separation

Goal: Avoid a Single Point Kill by Physical Separation of Redundant Functional Components

•

Example: Flight Control Computer





Multiple Physically Separate Units Are Inherently More Survivable Than a Single, Multi-channel Unit

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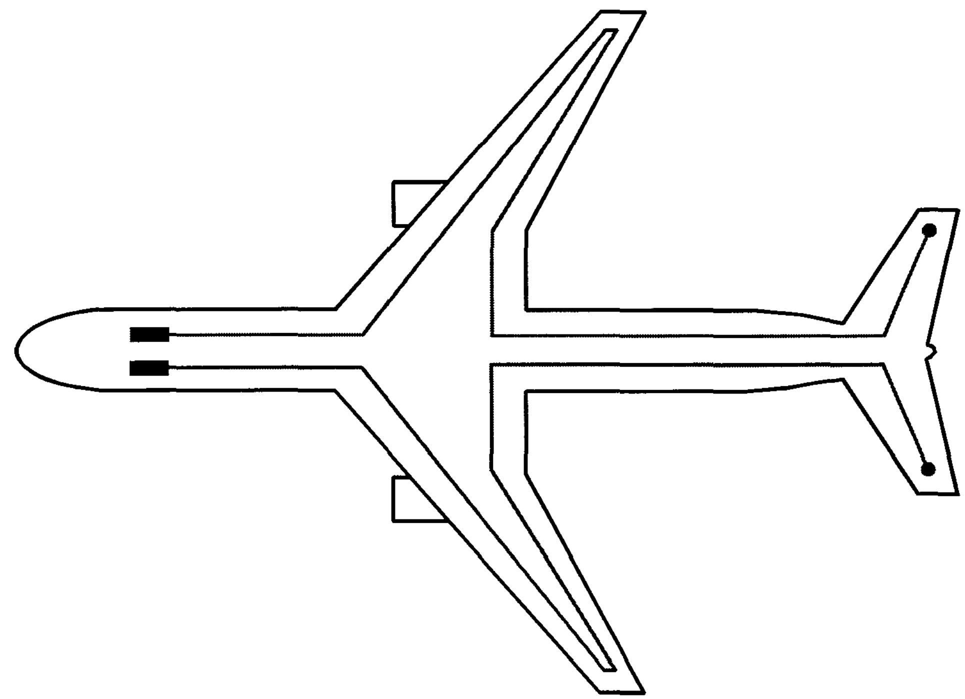
Component Redundancy With Separation

Goal: Avoid a Single Point Kill by Physical Separation of Redundant Functional Components

•

Example: Data Bus Wiring



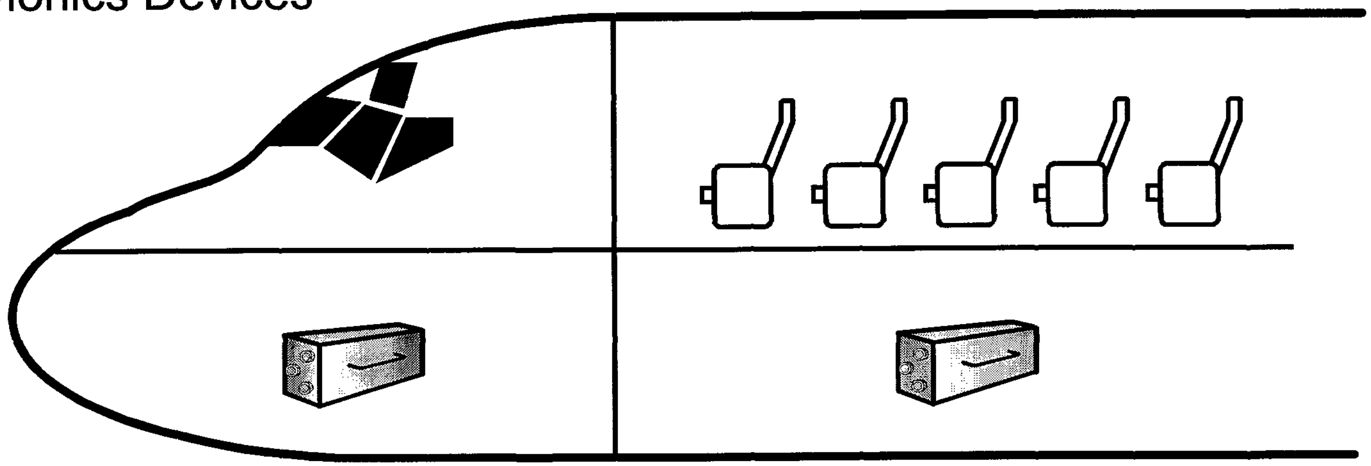
Multiple Data Bus Cables, Routed for Maximum Practical Separation

Component Location

Goal: To Position Components So That a Damage Mechanism Is Less Likely to Kill a Component

•

Example: Avionics Devices

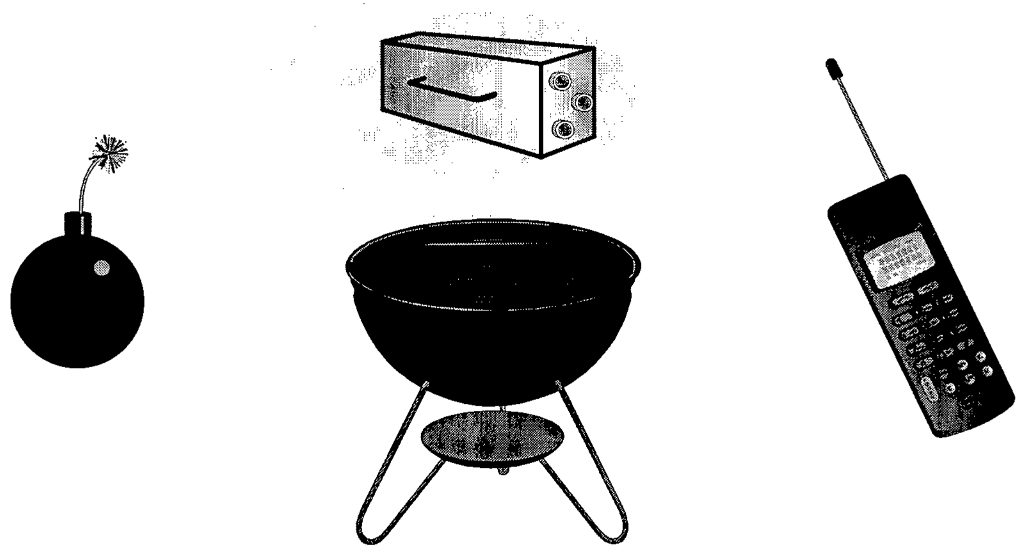


Box A Is Positioned Further Away From Possible Fire/Explosion in Cargo/Baggage or Passenger Compartments

Passive Damage Suppression

Goal: To Either Reduce Damage or Reduce the Effects of Damage

Example: Flight Data Recorder CNS Avionics



Design Avionics to Tolerate EMI, Fire and Blast Effects to the Extent Practicable

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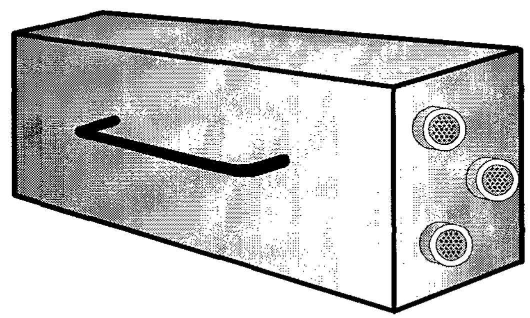
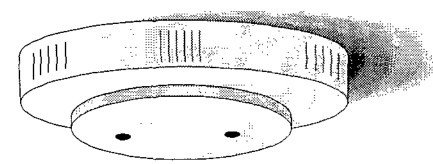
Active Damage Suppression

Goal: To Detect and Counter the Effects of a Damage Process (i.e., fire)

•

Example: Fire Detection and Extinguishing System





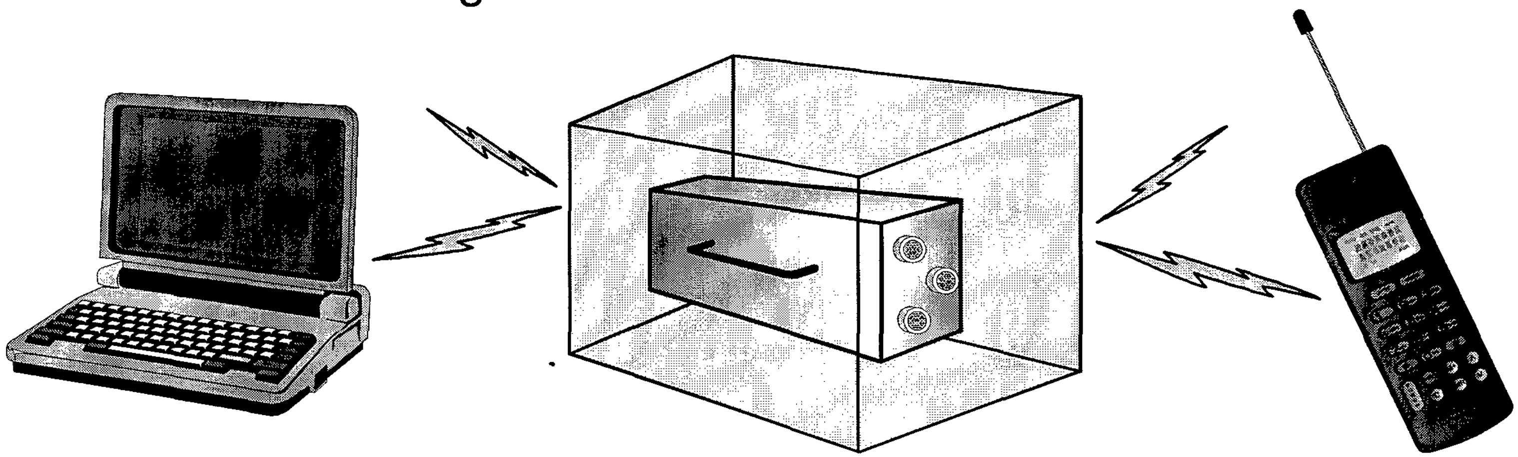
Avionics are Relatively Sensitive to Extremely High Temperatures

Component Shielding

Goal: Resist or Absorb the Damage Mechanisms by Using Coatings or Special Materials

•

Example: EMI/EMP Shielding



EMI Shielding Most Likely to Be Useful for Civil Aircraft

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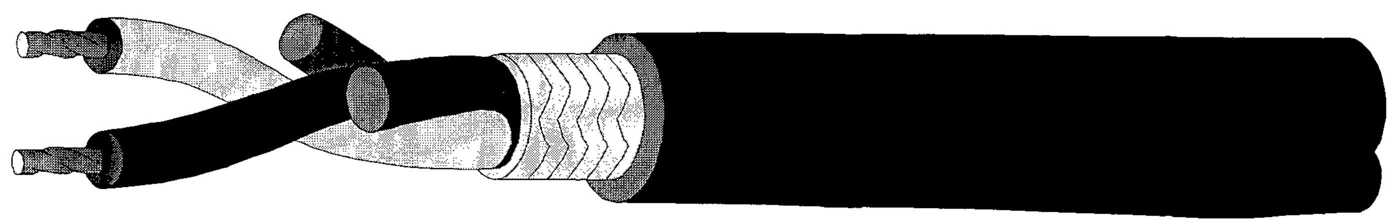
Component Elimination

Goal: Design Choices That Eliminate a Vulnerable Component or Replace It With Another, Less Vulnerable Component

•

Example: Data Bus Cable



Shielded Cables Add Weight, but Are Less Vulnerable to EMI, Blast and Fire

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Recommendations:

- Anticipate, Study and Prepare for the Threats
-
- Consider Use of Vulnerability Reduction Techniques When Designing:
    - Aircraft Systems
    - Avionics Components
    - Wiring and Cabling
    -
- Understand That Reliable, Fault Tolerant Avionics May Still Be Vulnerable

Augustine's Law XIV

After the Year 2015, There Will Be No Airplane Crashes.

There Will Be No Take Offs Either, Because Electronics Will Occupy 100 Percent of Every Airplane's Weight.

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All Aircraft Types
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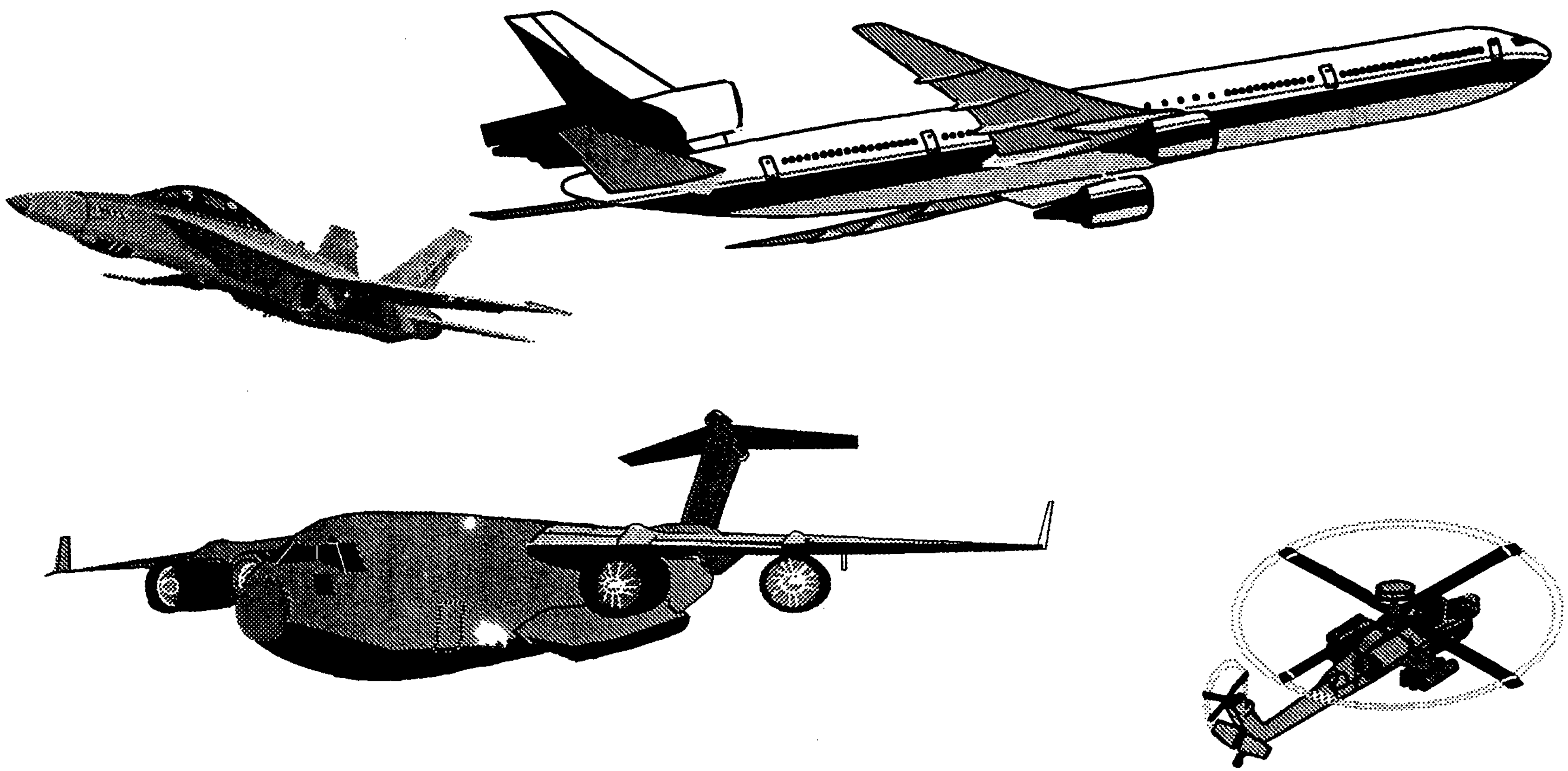
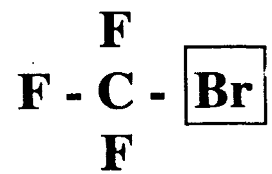


Applications

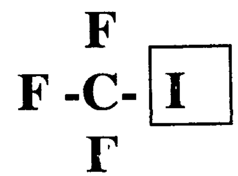
- Applications:
  - Engine Nacelles
  - Passenger / Crew
  - Lavatories
  - Cargo Bays
  - Dry Bays
  - Fuel Tanks

Leading Alternatives

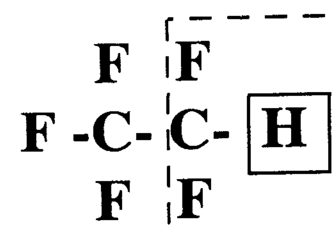
Baseline: HALON 1301 (CF_3Br)



Triodide: (CF_3I)

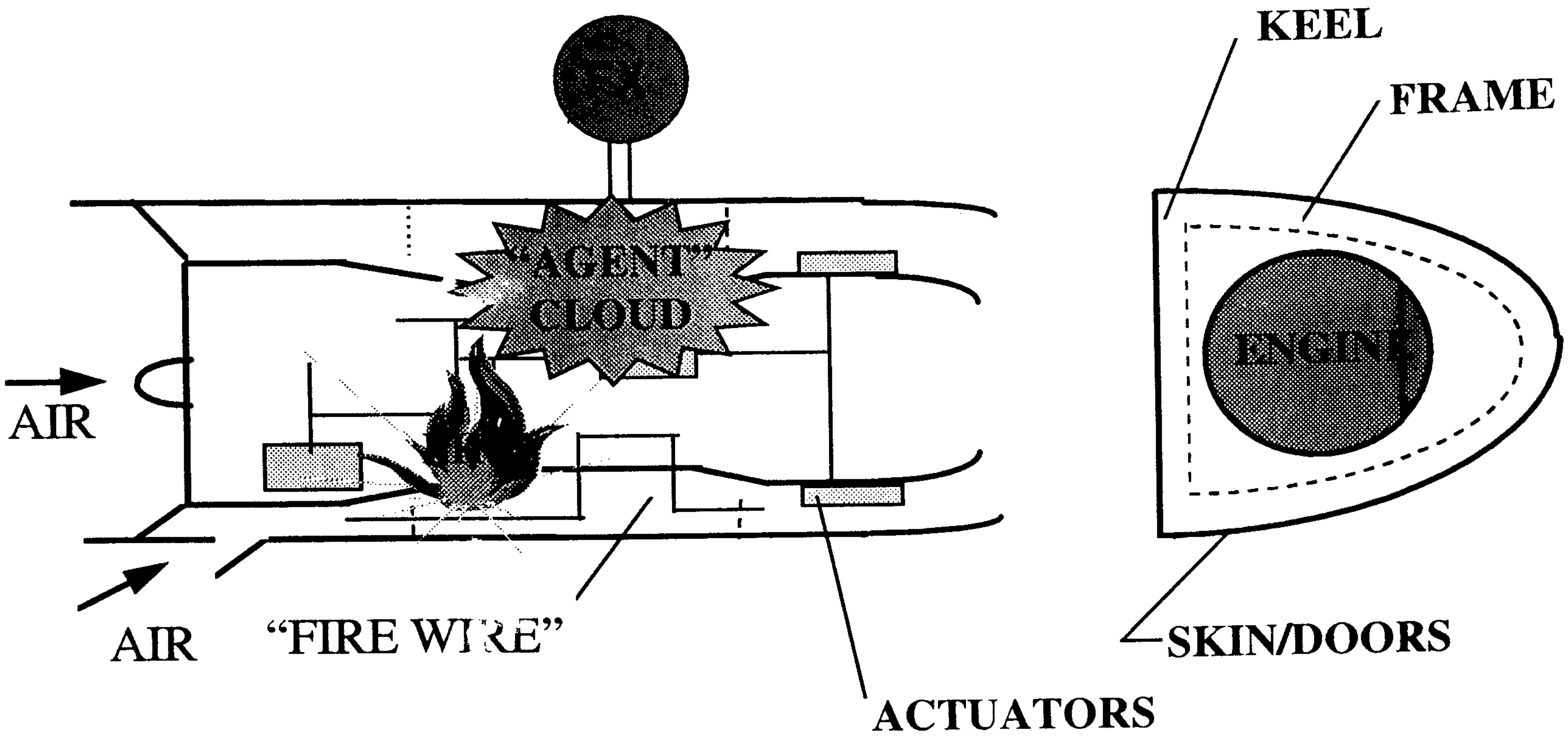


Fe-25: (C_2HF_5)

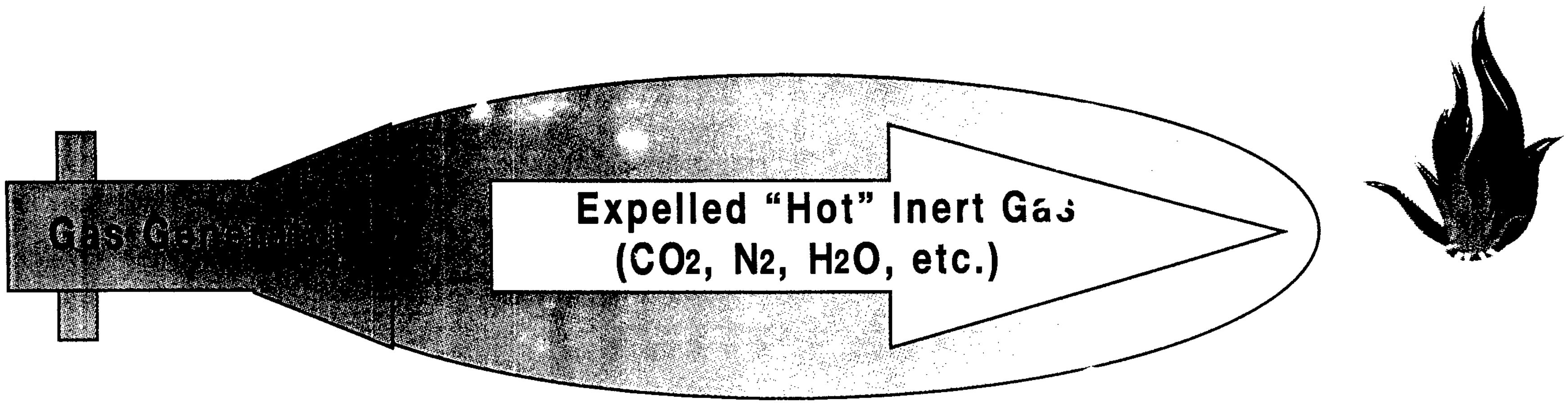


Solid Propellant Gas Generators: N_2, CO_2, H_2O, "Dust"

Engine Nacelle Protection



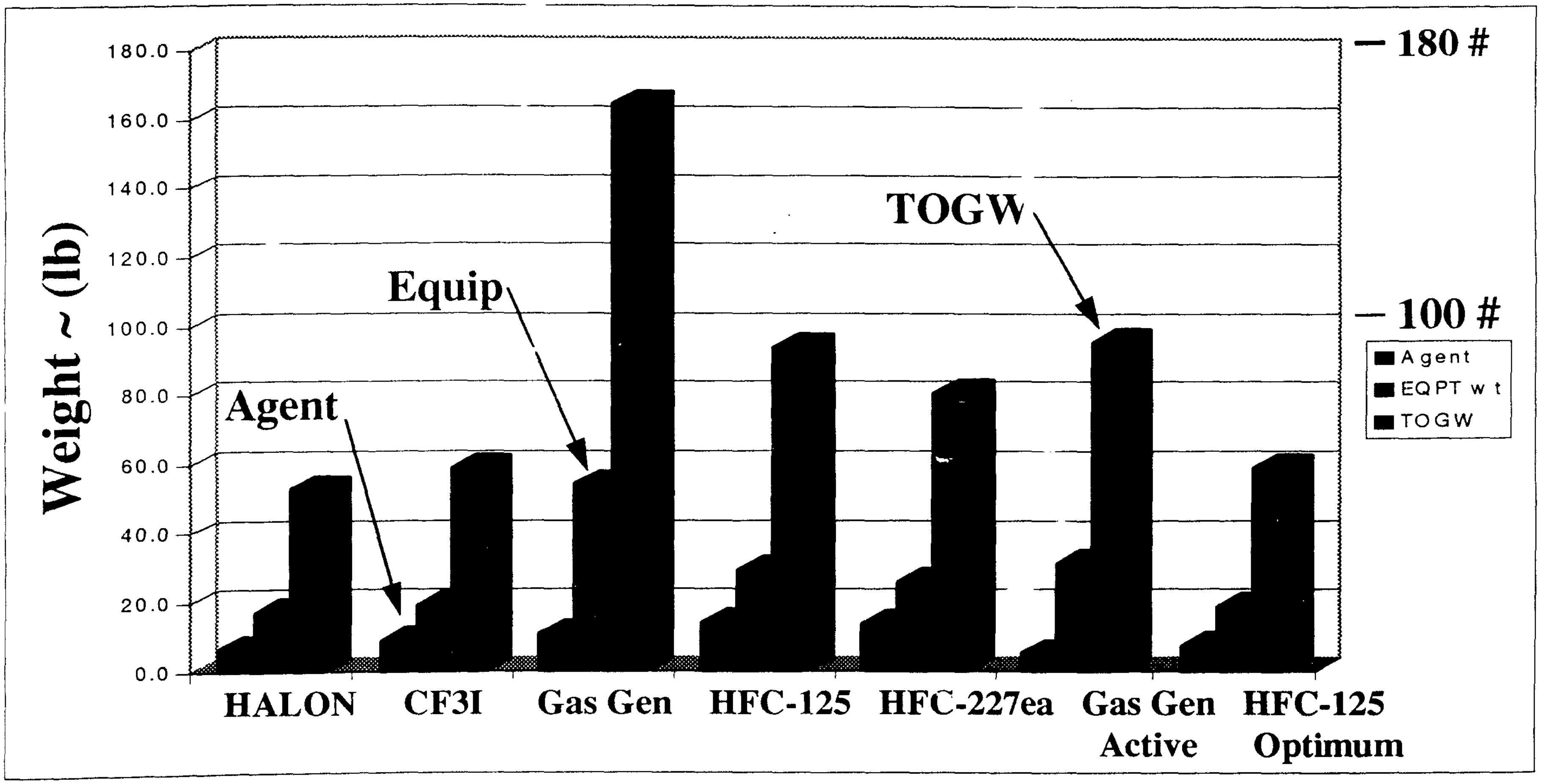
Solid Propellant Gas Generators



Other Alternatives

- "Water" Mist
- Hybrids (GG + FM-200 or "Active" Compounds)
- Advanced Agents
- Electric Field
- Several Candidates Have Had Little Aerospace Acceptance
  - Powders, Aerosols, Gels, etc.
  - Being Reconsidered
- PBr3

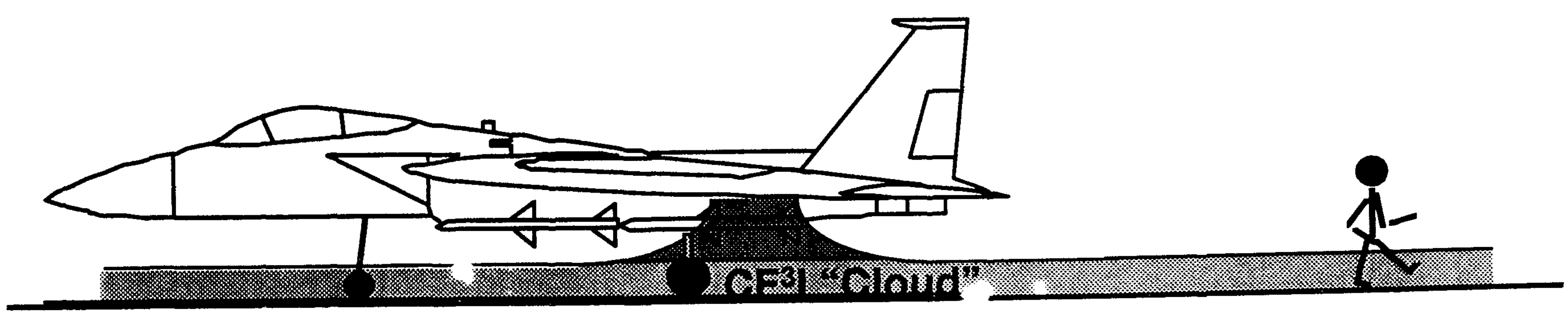
Updated Penalties



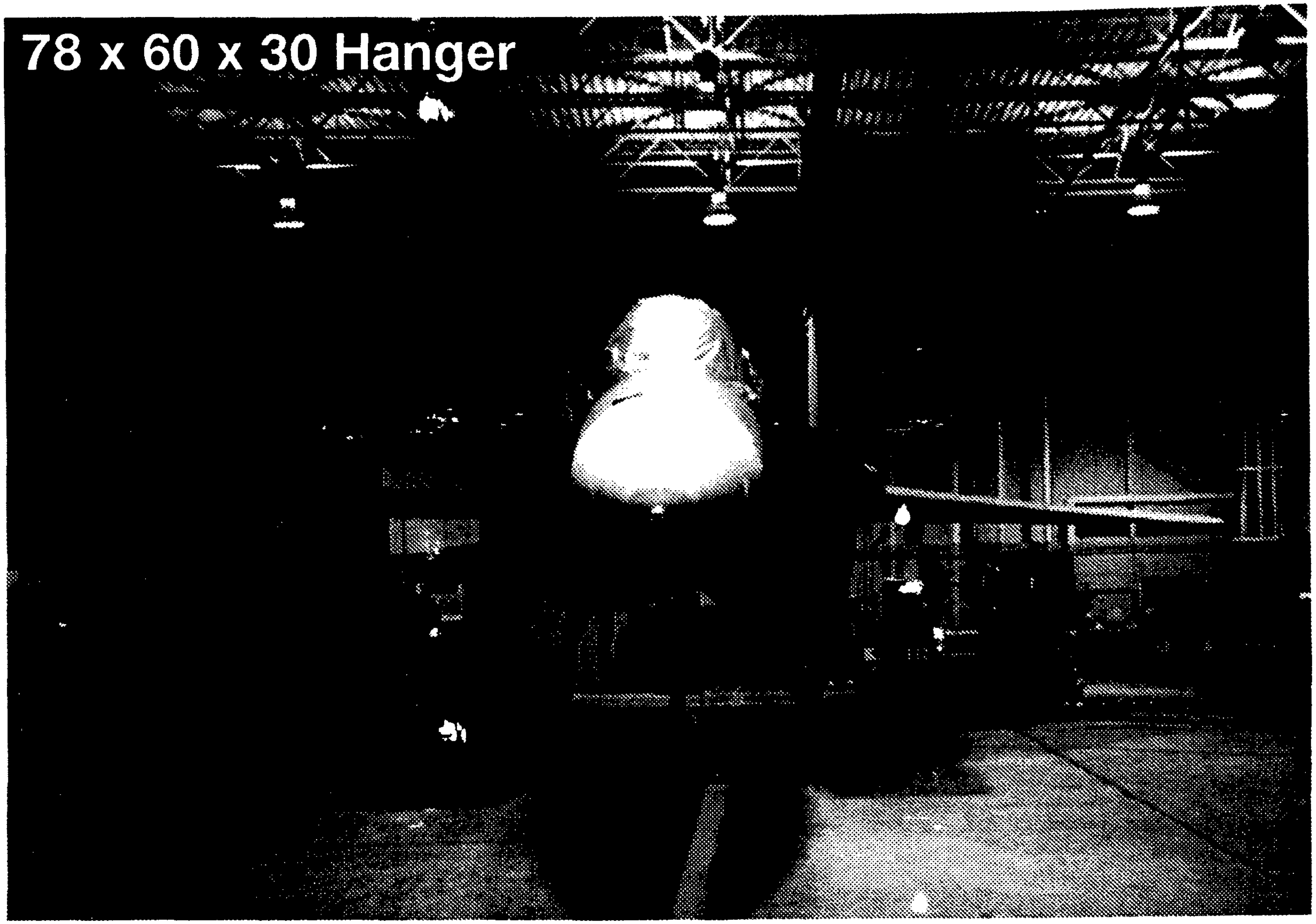
- Gas Generator: High Temp
- Active Gas Generator: High Temp, High Cost
- HFC-125: Full Scale Test Shows Promise

1997 Study

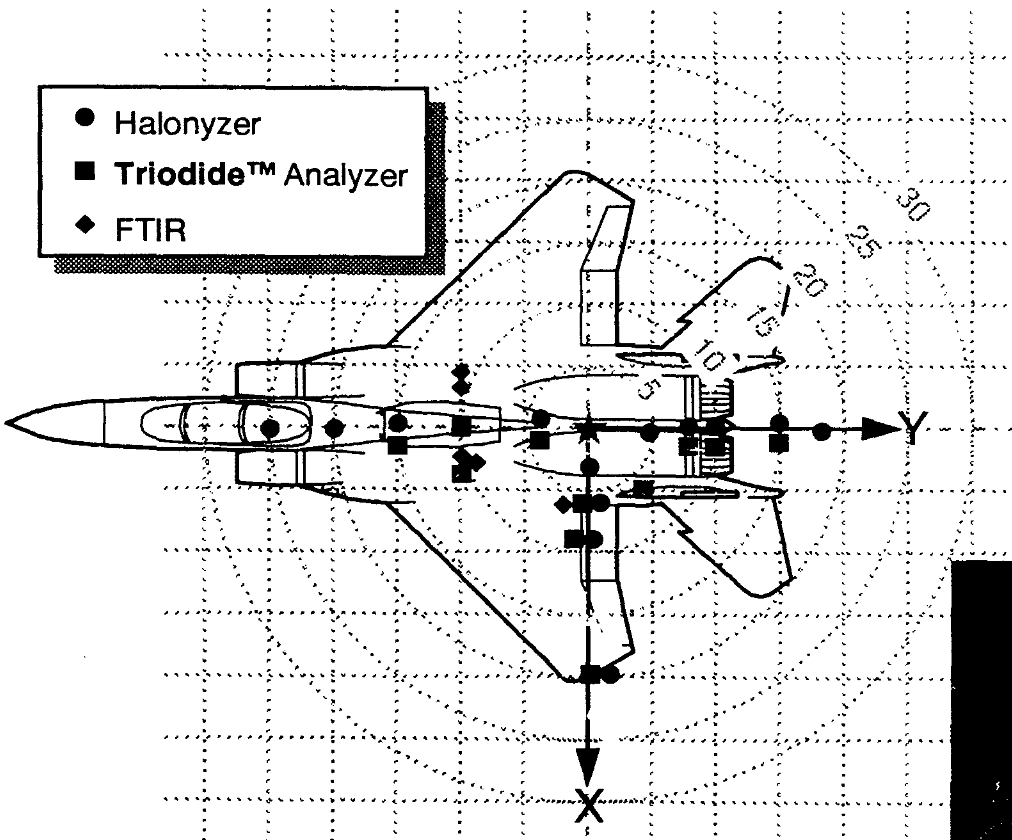
CF3I "Cloud" Shape / Height ?



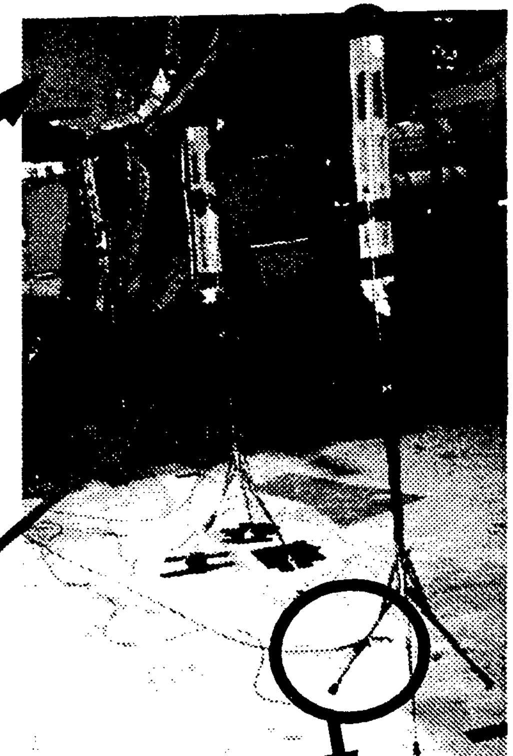
CF_3I Discharge Test 12/96



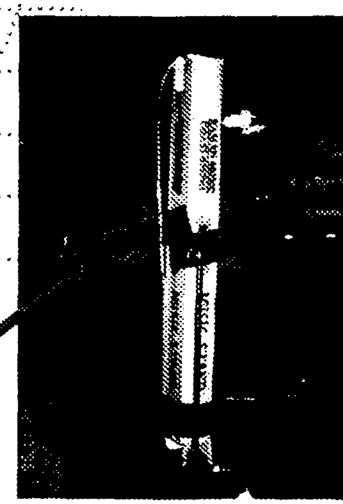
Open Nacelle - Sensor Coverage



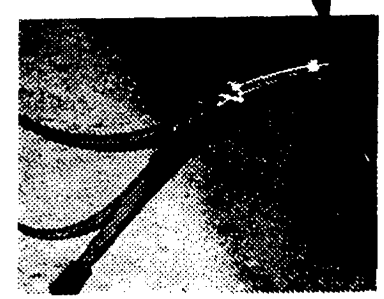
Aircraft in
78x60x30 ft.
Paint Hanger



Tygon Tubes
Transport Sample
Gas To Analyzer

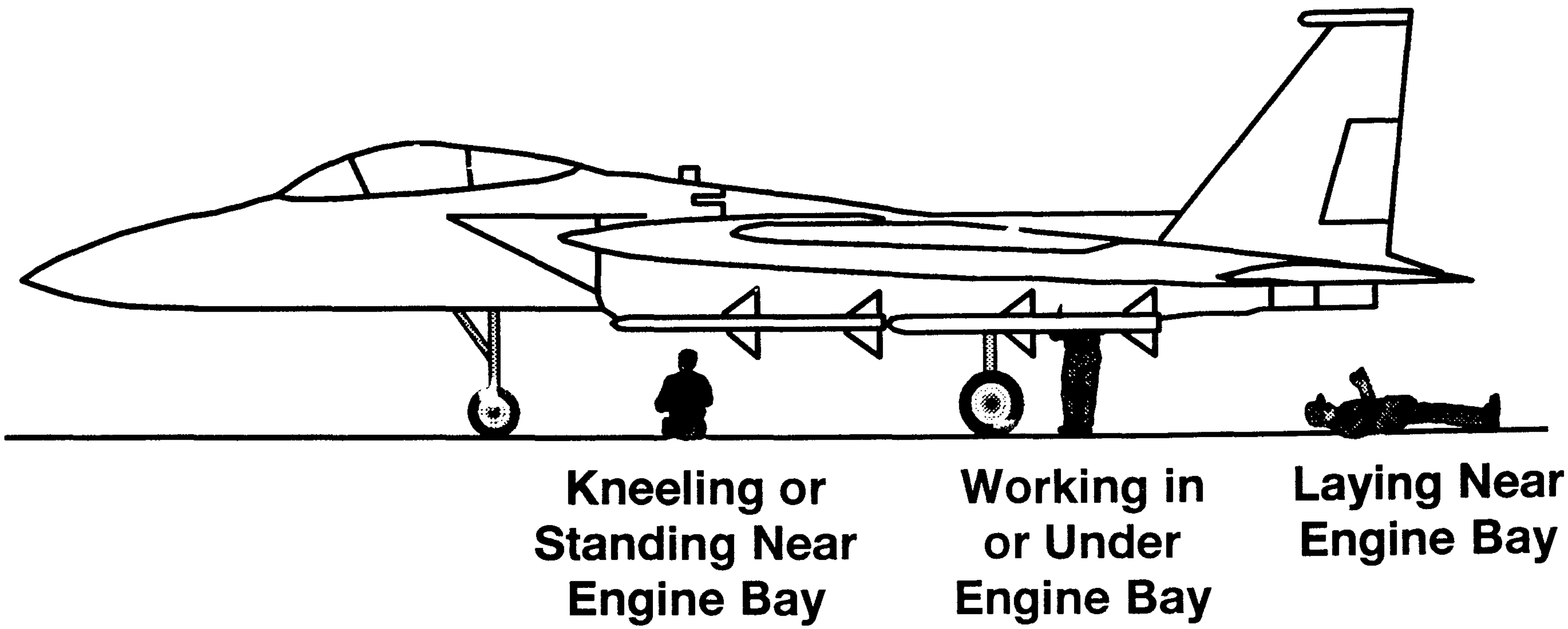


3 ft. & 5 ft. Sensors

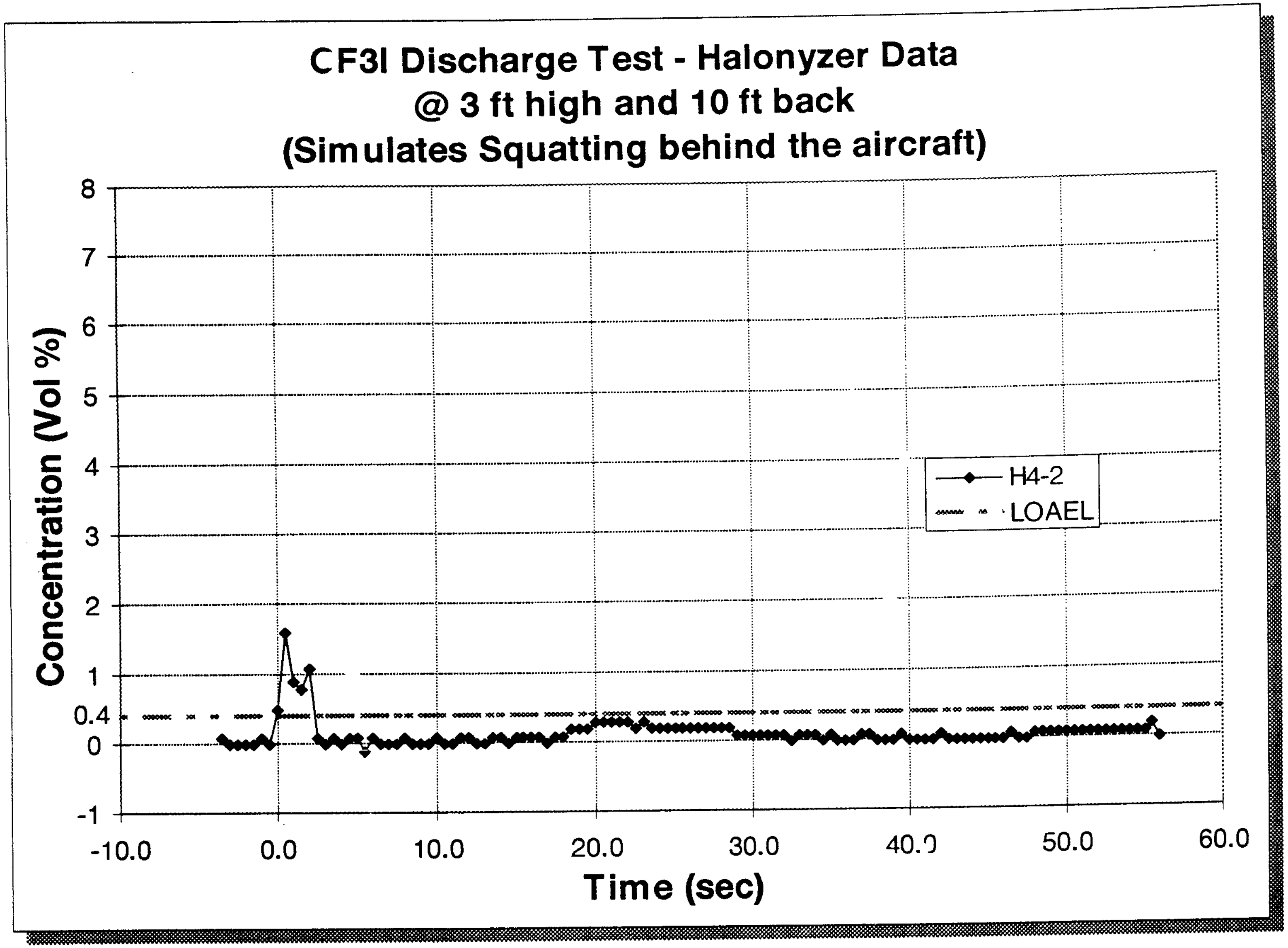


1/2 ft. Sensors

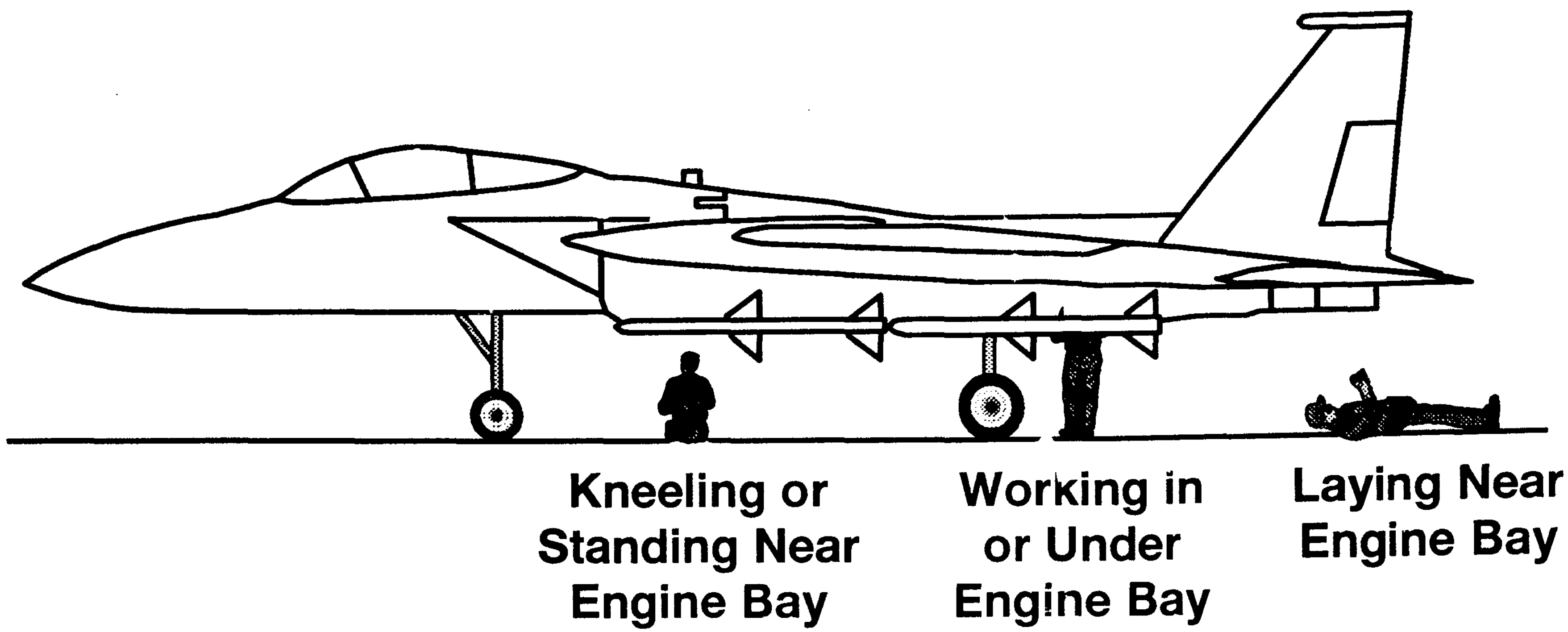
Crew Locations Considered



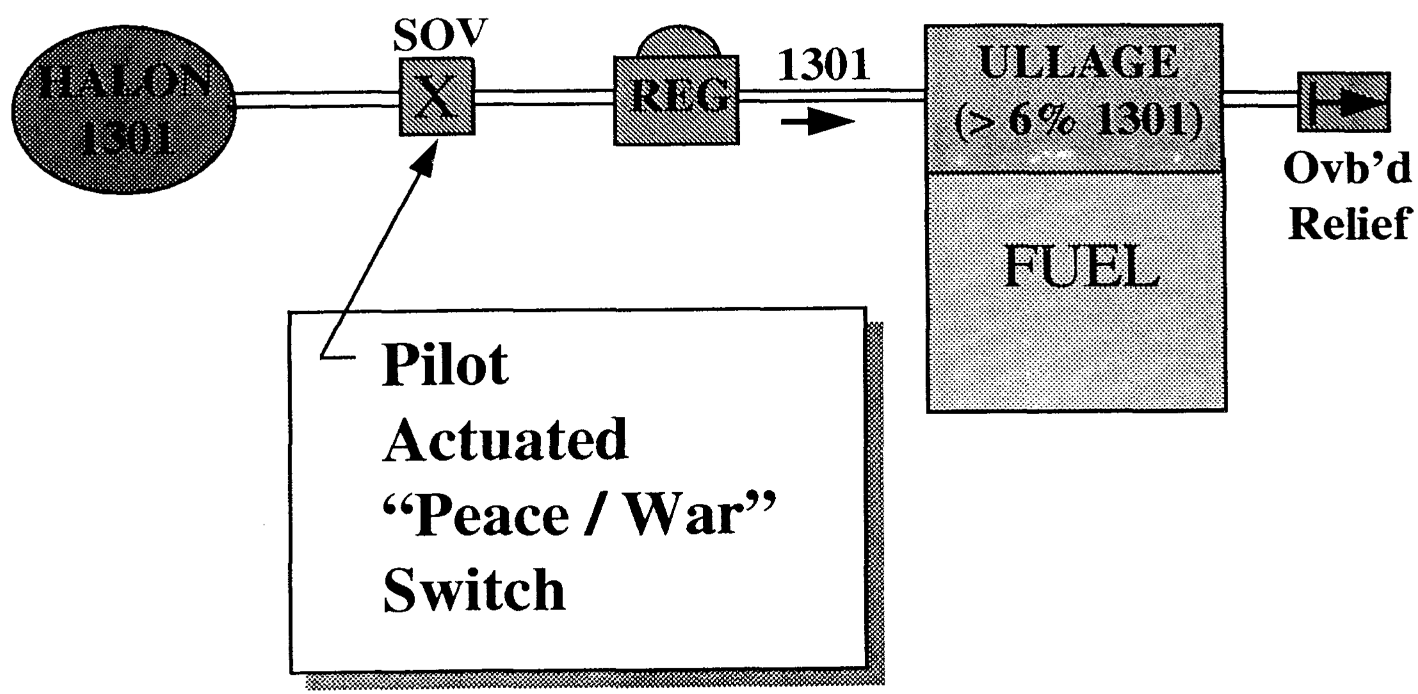
Highest Concentration Location
(Kneeling ***Outside*** the Nacelle)



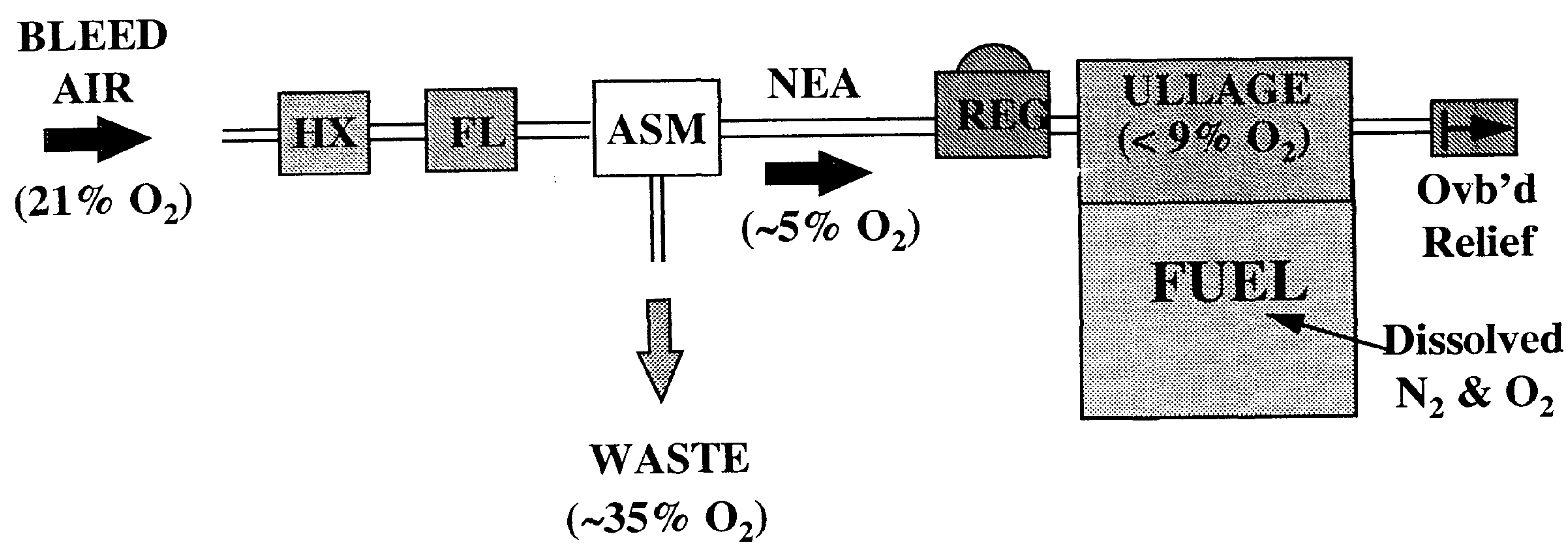
Crew Locations Considered



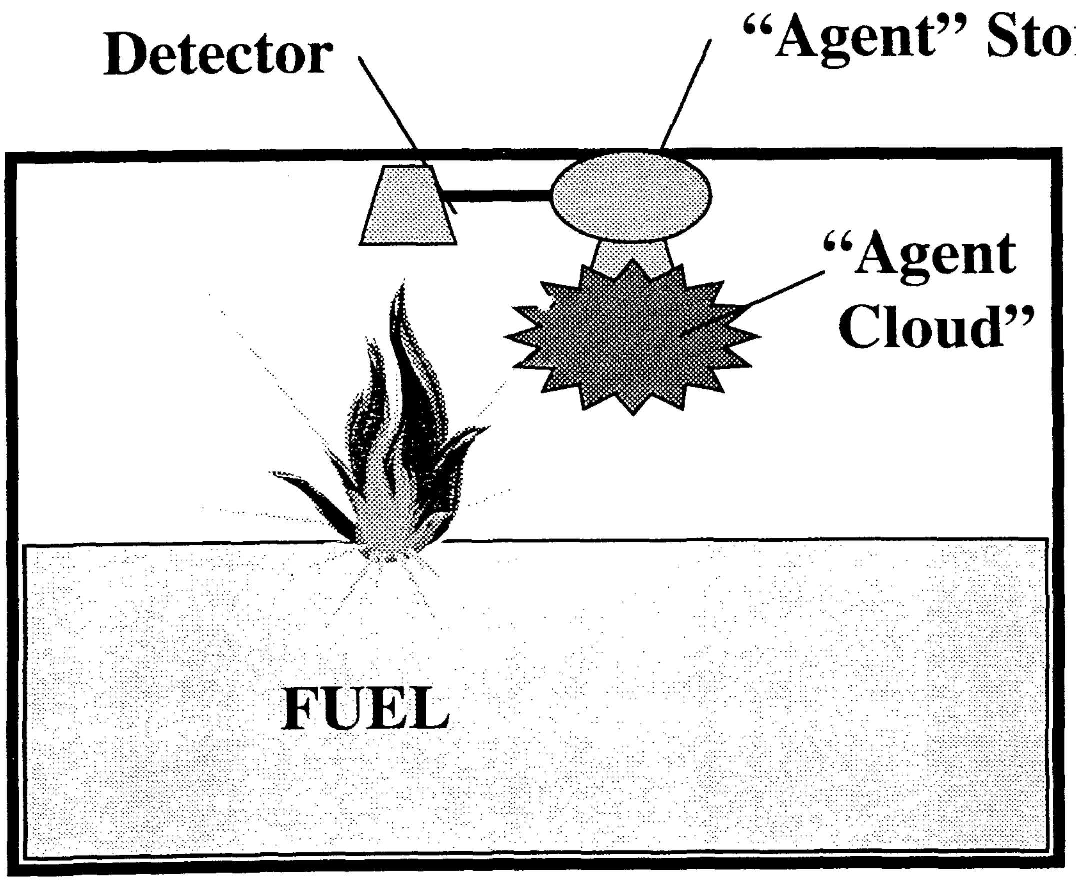
Fuel Tank Protection - HALON (or Similar "Agent")



Fuel Tank Protection - OBIGGS

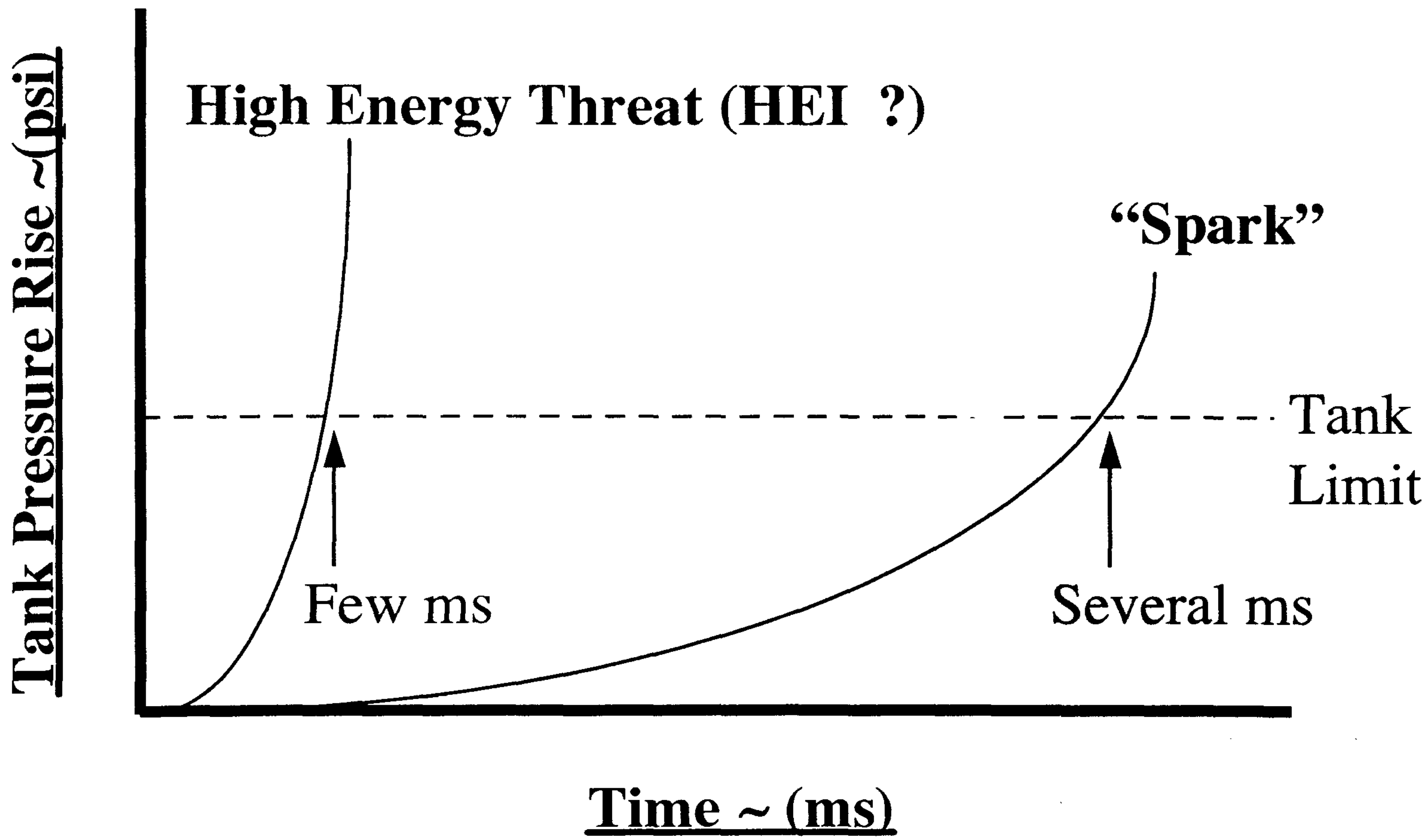


Detect / Suppress Tank Protection



Issues:
- Size of Threat
- Response Time
- Viewing Area
- "Full" Tank
- "Throw" Distance
- Geometry Limits
- "Clutter"

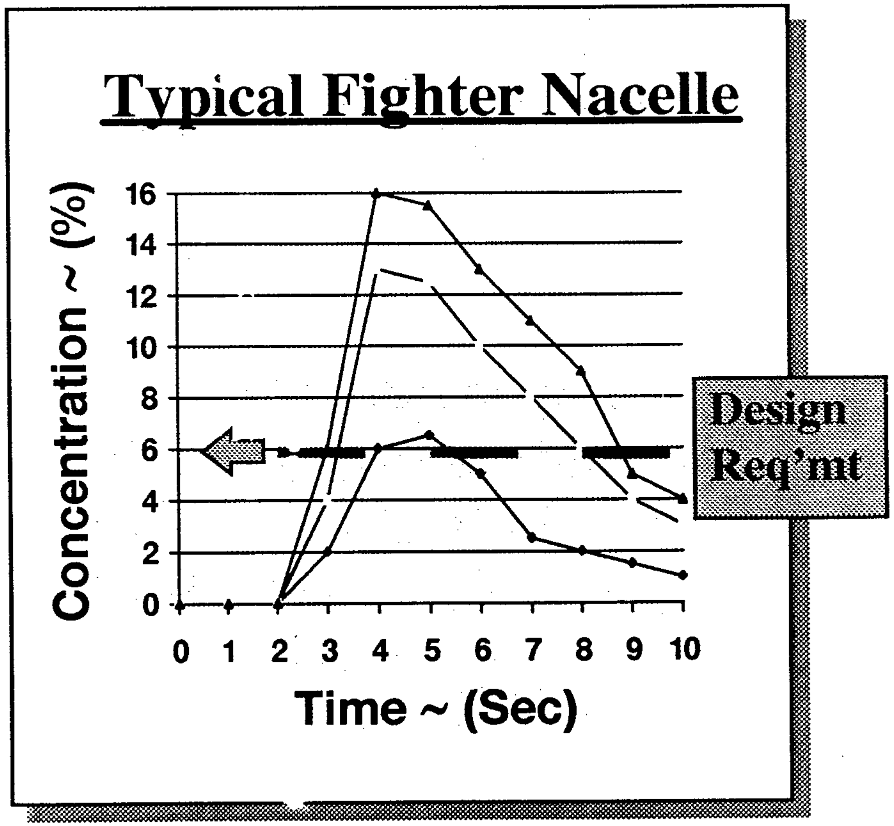
Fuel Tank Threat Effects



What Threat is "Best" Selected for Commercial Transports ??

Improved "Agent" Efficiency

- HALON 1301 Std:
  - Fixed Quantity & Test %
  - Concentration Usually OK
    - Simple Distribution
    - No Optimization Incentive
- Streaming Installations
  - "Old" USA More Complex
  - USSR 2402 More Complex
- USSR Fe-25 Test Data
- Unconventional Approaches



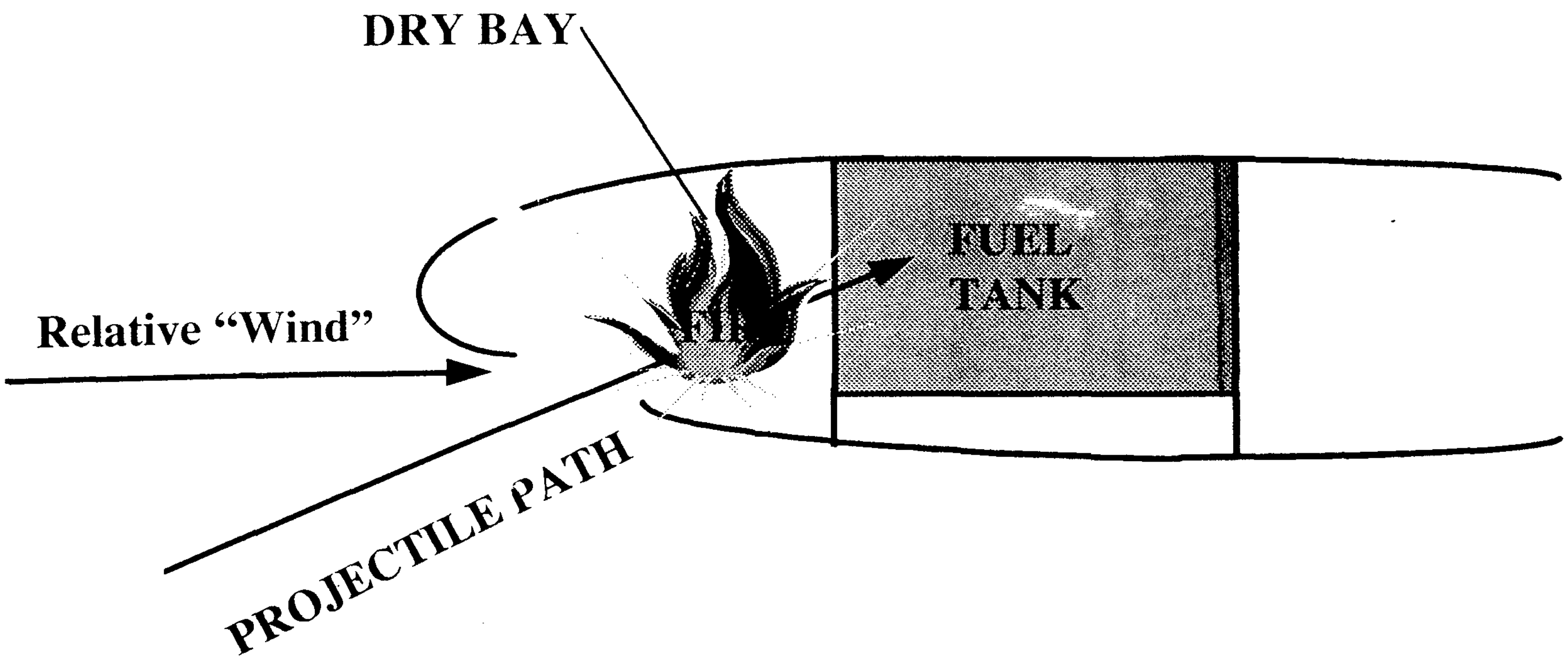
Can We Approach HALON Impacts by Optimizing Fe-25 ??

"Balanced" Hazards Evaluation

All Technologies Impose Some Human Hazard

	HALON 1301	Fe-25	Gas Gen	CF3I
"Surprise" Response	X	X	X	X
"Frostbite"	X	X		X
HF Effects		X		
"Hot" Exhaust			X	
"Dust" Impact			X	
Toxicity				X
Cardiac Sensitization				X
????				

Effect of "Equivalent Angle of Attack"



Should We Test @ Various Wind "Angles of Attack" ??

Material Compatibility

- Data on “Exotic” Eng/Airframe Mat’ls @ High Temperatures
  - Corrosion
  - Stress Corrosion, Hydrogen Embridelment, etc.
  - Salt Atmosphere, Salt Spray, SF, etc
- “Agents”
  - Fe-25, CF3I, 1301, etc.
  - Gas Generators (Std, Active)
  - Powders
- Exhaust Products
  - HF, HBr, etc.

Recommendations

Engine Nacelle

- More Efficient Dispersion of "Agents"
- Material Studies / Testing @ High Temperatures

Fuel Tank

- Commercial Threat Selection

Dry Bay

- Effect of "Angle of Attack"

General

- "Balanced" Evaluation of Alternatives & Associated Hazards
- Predictive Modeling
- Joint Military / Commercial Applications
- Continue "Next-Generation" Program


ALTERNATIVES TO HA
A STATUS REPORT
PRESENTED AT THE ADPA/NSIA SYMPOSIUM
ENHANCING AIRCRAFT SURVIVABILITY -
A VULNERABILITY PERSPECTIVE
OCTOBER 21 - 23, 1997
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA
PRESENTED BY
MATT KOLLECK
BOOZ•ALLEN & HAMILTON INC


OVERVIEW
◆ SHORT HISTORY
◆ HALON REPLACEMENT PROGRAM FOR AVIATION
◆ OTHER PROGRAMS
◆ COSTS OF FIRE LOSSES
◆ CONCLUSIONS

SHORT HISTORY

- MONTREAL PROTOCOL LIMITED PRODUCTION OF OZONE DEPLETING SUBSTANCES (ODS)
- SUBSEQUENT INTERNATIONAL AGREEMENTS AND NATIONAL LEGISLATION HAVE DICTATED THE PHASE-OUT OF ODS PRODUCTION
- USAGE OF EXISTING SUPPLIES WAS STILL OK
- ODS PRODUCTION STOPPED IN THE U.S. 1/1/94
- ODS INCLUDE HALONS
- USAF DECIDED IN 1992 TO DEVELOP A NON-OZONE DEPLETING SOLUTION BY 1995

HALON REPLACEMENT PROGRAM FOR AVIATION

- JOINT DOD/FAA PROGRAM TO IDENTIFY AND EVALUATE ALTERNATIVE EXTINGUISHING AGENTS
- DRY BAY AND ENGINE NACELLE APPLICATIONS
- THREE-PHASED PROGRAM
  - OPERATIONAL PARAMETERS STUDY
    - WHAT FIRE ZONE PARAMETERS ARE IMPORTANT
  - OPERATIONAL COMPARISON OF SELECTED AGENTS
    - HEAD-TO-HEAD COMPETITION BETWEEN AGENTS
  - ESTABLISHMENT OF DESIGN CRITERIA METHODOLOGIES
    - DEVELOP DESIGN EQUATIONS FOR THE NEW AGENT
- LAB-SCALE TESTING CONDUCTED AT NIST
- FULL-SCALE TESTING CONDUCTED AT WL

HALON REPLACEMENT PROGRAM FOR AVIATION - OUTPUTS

- RECOMMENDED REPLACEMENT AGENT
  - HFC-125 FOR BOTH APPLICATIONS
- EIGHT TECHNICAL REPORTS
  - PHASE I REPORTS AVAILABLE NOW
  - PHASE II REPORTS AND DESIGN GUIDES CLOSE
  - PHASE III REPORTS ARE DRAFTED AND GOING THROUGH THE FIRST ITERATION
- DATA BASE OF FIRE ZONE PARAMETER VALUES
- INCIDENT DATA ANALYSIS REPORT
- HALON DISCHARGES AT ALTITUDE REPORT
- THE EFFECTS OF CLUTTER ON FIRE DEVELOPMENT REPORT

OTHER PROGRAMS

- WRIGHT LAB F-22 ENGINE NACELLE TEST
  - UTILIZED SOLID PROPELLANT GAS GENERATOR (SPGG) TECHNOLOGY
  - TESTING COMPLETED
  - DRAFT/FINAL REPORT BY END OF NOVEMBER 1997
  - SEE POSTER PRESENTATION HERE AT SYMPOSIUM
- NAVAL AIR WARFARE CENTER - CHINA LAKE F/A-18 E/F ENGINE NACELLE TESTING
  - UTILIZED SPGG TECHNOLOGY
  - DOCUMENTED IN NAWCWPNS TM 7859, MARCH 1995
- NEXT GENERATION FIRE SUPPRESSANT TECHNOLOGY PROGRAM (NGP)
  - HEADED BY DR. DICK GANN AT NIST
  - GOAL IS TO DEVELOP EFFECTIVE, ENVIRONMENTALLY FRIENDLY FIRE SUPPRESSION TECHNIQUES BY 2004

COSTS OF FIRE AND FIRE PROTECTION TO THE USAF

- ESTIMATED HISTORICAL COSTS ($95) FOR THE PERIOD 1966 THROUGH 1995 - $15.465 B
  - COSTS OF PEACETIME LOSSES - $9.271 B
  - COSTS OF COMBAT LOSSES - $5.878 B
  - COSTS OF R&D - $0.316 B
- PROJECTED COSTS ($96) FOR THE PERIOD 1996 THROUGH 2025 - $15.990 B
  - COSTS OF PEACETIME LOSSES - $12.558 B
  - COSTS OF COMBAT LOSSES - $2.868 B
  - COSTS OF R&D - $0.564 B

BENEFITS OF FIRE PROTECTION - GREATER THAN THE COSTS

- COST/BENEFIT ANALYSIS PERFORMED
- BENEFITS TO THE USAF TAKEN FROM A STUDY CONDUCTED BY THE ASC SAFETY OFFICE
  - $700 M OVER A 25-YEAR PERIOD
- COSTS DEVELOPED PREVIOUSLY
- NET PRESENT VALUE OF $119 M OVER NEXT 30 YEARS
  - PROBABLY UNDERSTATED AS MORE EXPENSIVE AIRCRAFT ENTER THE INVENTORY


CONCLUSIONS
FIRES ARE COSTLY EVENTS
RESTRICTIONS ON HALONS ONLY GOING TO GET WORSE
CURRENT RECOMMENDED REPLACEMENT IS HFC-125
PROGRAMS UNDERWAY TO DEVELOP LONG TERM SOLUTION

JTCG/AS

INTEGRATED SURVIVABILITY ASSESSMENT: MEASURING THE BALANCE

David H. Hall
Naval Air Warfare Center, Weapons Division
China Lake, CA

BRIEFING SYNOPSIS:

INTEGRATED SURVIVABILITY ASSESSMENT: MEASURING THE BALANCE

DAVID H. HALL
NAWCWPNS

Measuring the balance between vulnerability and susceptibility technologies is a critical element in designing aircraft for survivability. But in order to measure that balance, a complete set of credible analytical tools needs to be available and accepted within the Joint Service community.

A workshop was held in May of this year, in Albuquerque, NM, whose objectives were: developing a common definition of Integrated Survivability Assessment (ISA), identifying customer requirements for survivability assessment, determining the need for ISA capabilities, understanding the contribution to those requirements from ongoing initiatives (such as JMASS and HLA), identifying shortfalls, and developing the start of a roadmap for the JTCG/AS to fill those shortfalls. This briefing will discuss the results of the workshop and their application to Joint survivability methodology development "into the next century."

A fairly significant number of "customers" at the workshop indicated that they require the ability to assess the military worth of weapons systems, and that survivability, as one part of an integrated assessment, needs to be addressed in a mission context. The ISA Workshop developed a list of requirements for the JTCG/AS to pursue, including the credibility of engagement level simulations (including Pk), mission level survivability modeling, and the inclusion of mission effectiveness and cost assessment in the analysis process. The output of the workshop provided guidance for defining the elements to include in a roadmap for future JTCG/AS activities, as well as actions to take with regard to JMASS developments and HLA.

slides

OVERVIEW

- **CREDIBLE INTEGRATED SURVIVABILITY ASSESSMENTS ARE KEY TO THE ACQUISITION OF SURVIVABLE WEAPONS SYSTEMS**
  - We can't evaluate design tradeoffs without them

- **THOSE ASSESSMENTS ARE SELDOM DONE IN A MANNER THAT ADEQUATELY TRADES ALL SURVIVABILITY DESIGN OPTIONS**
  - EW, LO, Vulnerability, etc.
  - Results in less effective, more costly systems
  - In other words, we can't really agree on how to do systems engineering analysis for survivability
    - » What is the proper balance between vulnerability and susceptibility reduction features?

- **THE JOINT COMMUNITY (JTCG/AS) IS ADDRESSING THE PROBLEM:**
  - Integrated Survivability Assessment Workshop
  - Methodology Roadmap

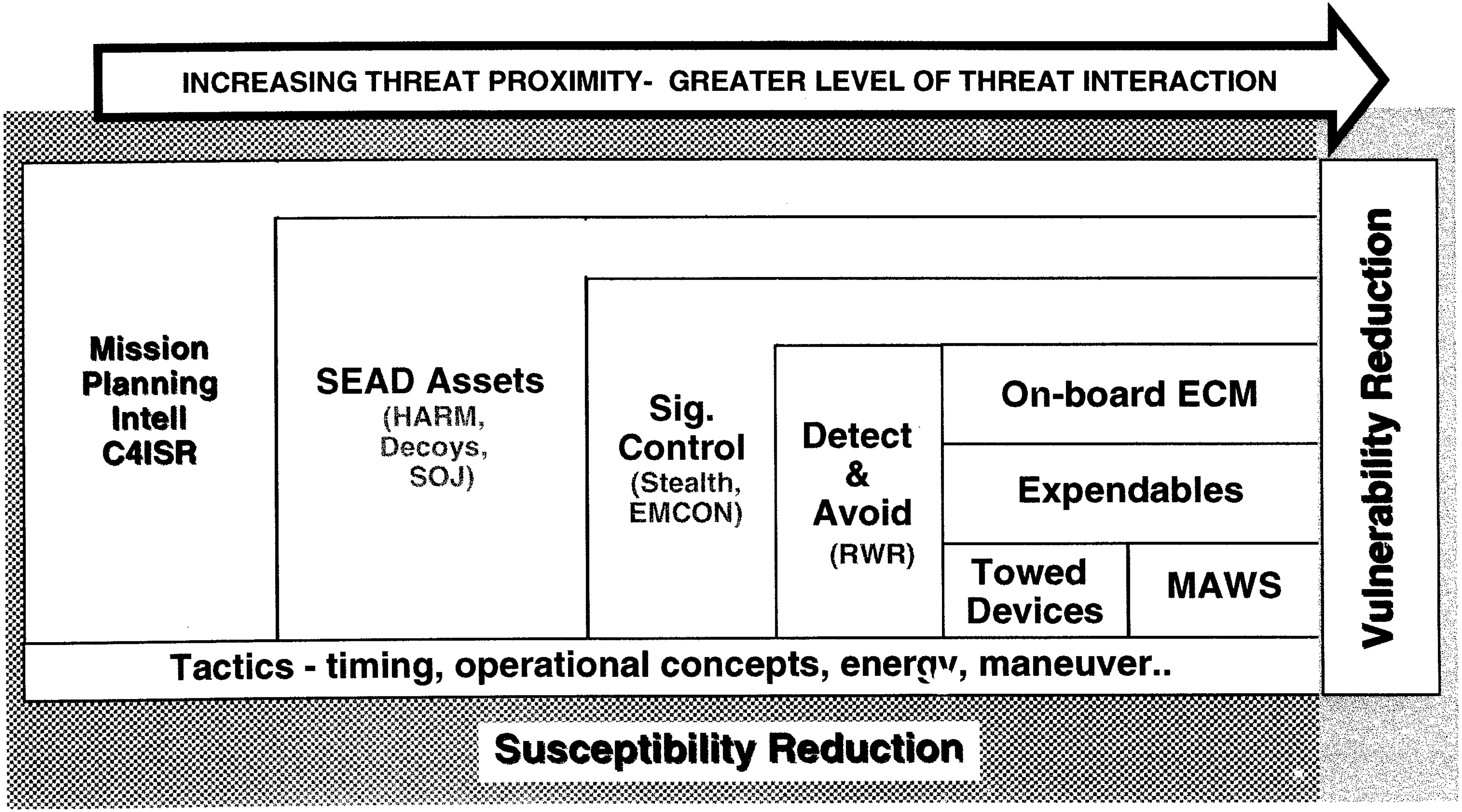
- **AND WE NEED YOUR HELP**

WHY IS INTEGRATED SURVIVABILITY ASSESSMENT CRITICAL?

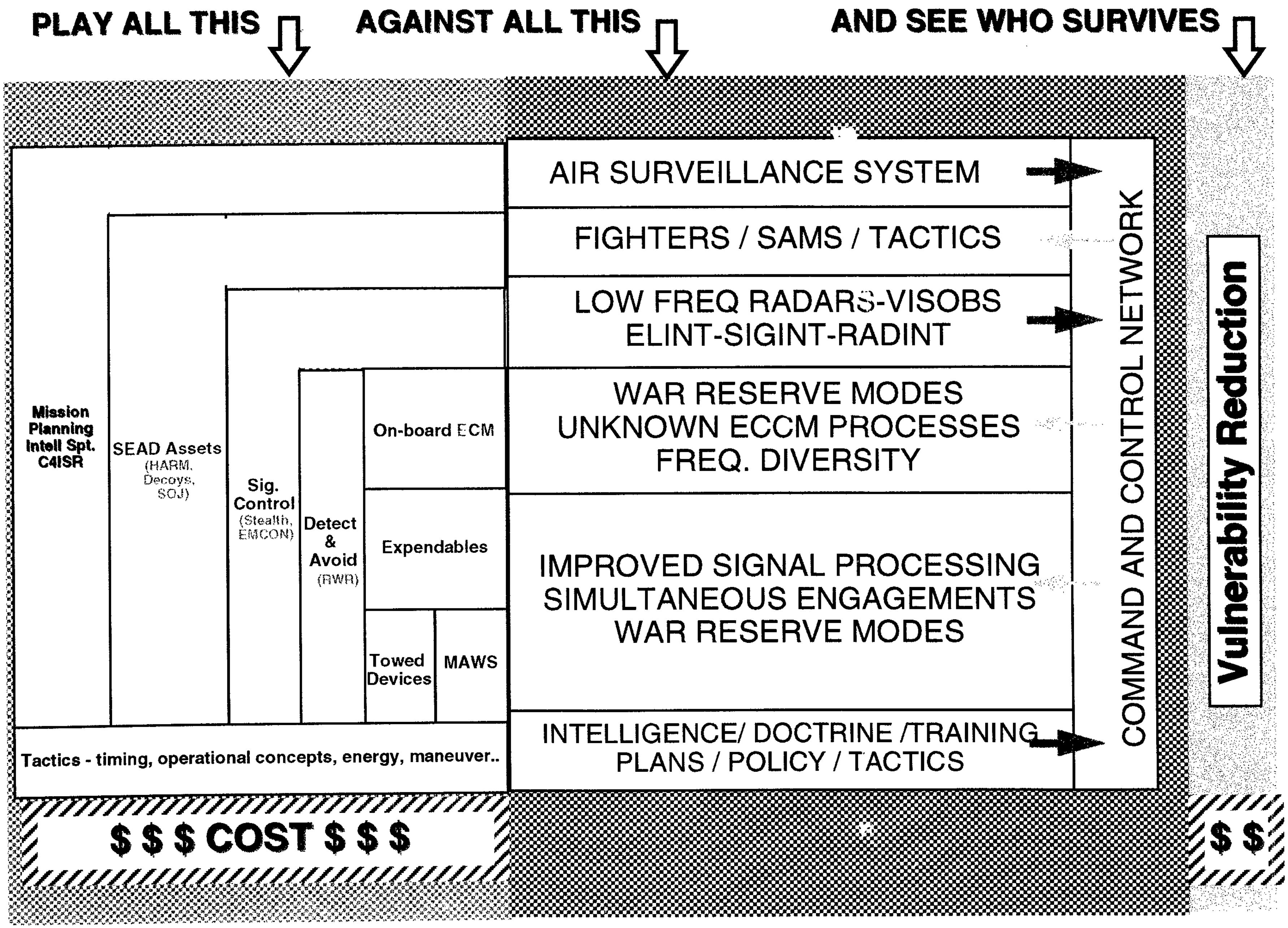
- **SURVIVABILITY IS A KEY DESIGN DISCIPLINE AND COST DRIVER FOR AIR WEAPONS SYSTEMS**
- **MORE AND MORE EMPHASIS PLACED ON M&S IN THE AIR WEAPONS SYSTEM DESIGN PROCESS**
  - » Needed for requirements definition, specification development, system design, T&E & training
- **<u>INTEGRATED SURVIVABILITY ASSESSMENT:</u>**
  - » Reduces risk and cost in acquisition
  - » Ensures survivability performance
  - » Supports definition of realistic, supportable and cost-effective requirements

PINPOINTS MOST COST-EFFECTIVE SURVIVABILITY TECHNOLOGIES FOR SYSTEM DESIGN

SURVIVABILITY SPECTRUM



INTEGRATED SURVIVABILITY ASSESSMENT (ISA)



JTCG/AS GOAL: INTEGRATED SURVIVABILITY ASSESSMENT

- **A standard methodology for design, development, T&E to include all aspects of survivability**
- **Facilitating evaluation of an air vehicle's ability to survive in an integrated air defense system environment**
  - **Can the aircraft survive to perform its mission?**
  - Considering all onboard and "offboard" assets
    - » Including all support assets: Fighter support, SEAD (SOJ & HARM,TALD), etc.
  - Considering all threat assets
    - » IADS, GCI, Fighters, SAMs, GUNs, ...
- **Distributed through the Survivability/Vulnerability Information Analysis Center (SURVIAC)**

JTCG/AS ISA WORKSHOP

- **May 1997 in Albuquerque**
  - Sponsored by JTCG/AS and AFOTEC
- **Identified acquisition "Customer" needs for Integrated Survivability Assessment**
  - Good participation from OT, DT communities
    - » OSD, Services, Industry
- **Identified strengths and shortfalls in current M&S initiatives to satisfy those needs**
  - JMASS, HLA, DIME, etc.
- **Developed a roadmap to fill those shortfalls**
  - For the JTCG/AS

ISA WORKSHOP ORGANIZATION

- ISA DEFINITION
- REQUIREMENTS
- CURRENT INITIATIVES
- SHORTFALLS
- ROADMAP

INTEGRATED SURVIVABILITY ASSESSMENT: A DEFINITION

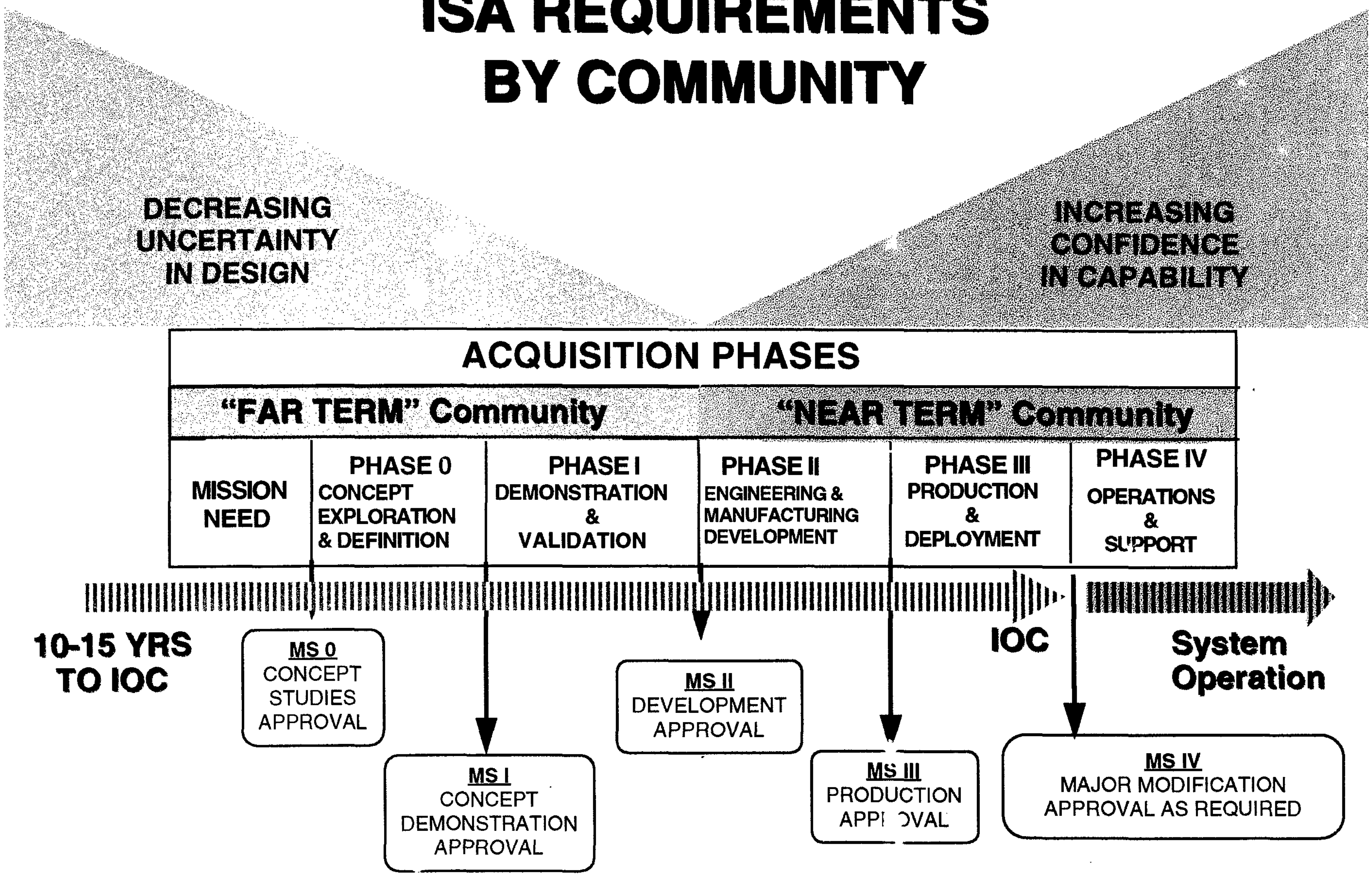
A consistent process that combines, into an integrated whole, all the component parts of the survivability equation to support:

- Survivability design based on mission effectiveness and cost goals
- Accounting for the impact of increasing survivability on mission effectiveness
- Real world operational requirements used in survivability risk assessment and trade off studies

INTEGRATED SURVIVABILITY ASSESSMENT

- **Integrated Systems**
  - Conceptual view of “us” as a coherent organized system versus “them” as a coherent and organized system
- **Integrated Models**
  - M&S Technology serving the assessment process by facilitating the comparison of Integrated Systems
- **Integrated Process**
  - Analysis supporting all phases of system development

ISA REQUIREMENTS BY COMMUNITY



REQUIREMENTS FOR ISA

- **Consensus within "Near Term" and "Far Term" communities**
  - > NEAR TERM USERS
    - » For OT programs: high fidelity missile flyout, vulnerability and endgame models
  - > FAR TERM USERS
    - » For Requirements and DT(and DOT&E): mission level assessments of military worth
- **However, less agreement between communities**
  - » OT focused on engagements with current threat systems
  - » DT focused on mission & campaign level, emerging threats
  - » Campaign Planners, CINCs not represented

ASSESSMENT OF CURRENT M&S INITIATIVES

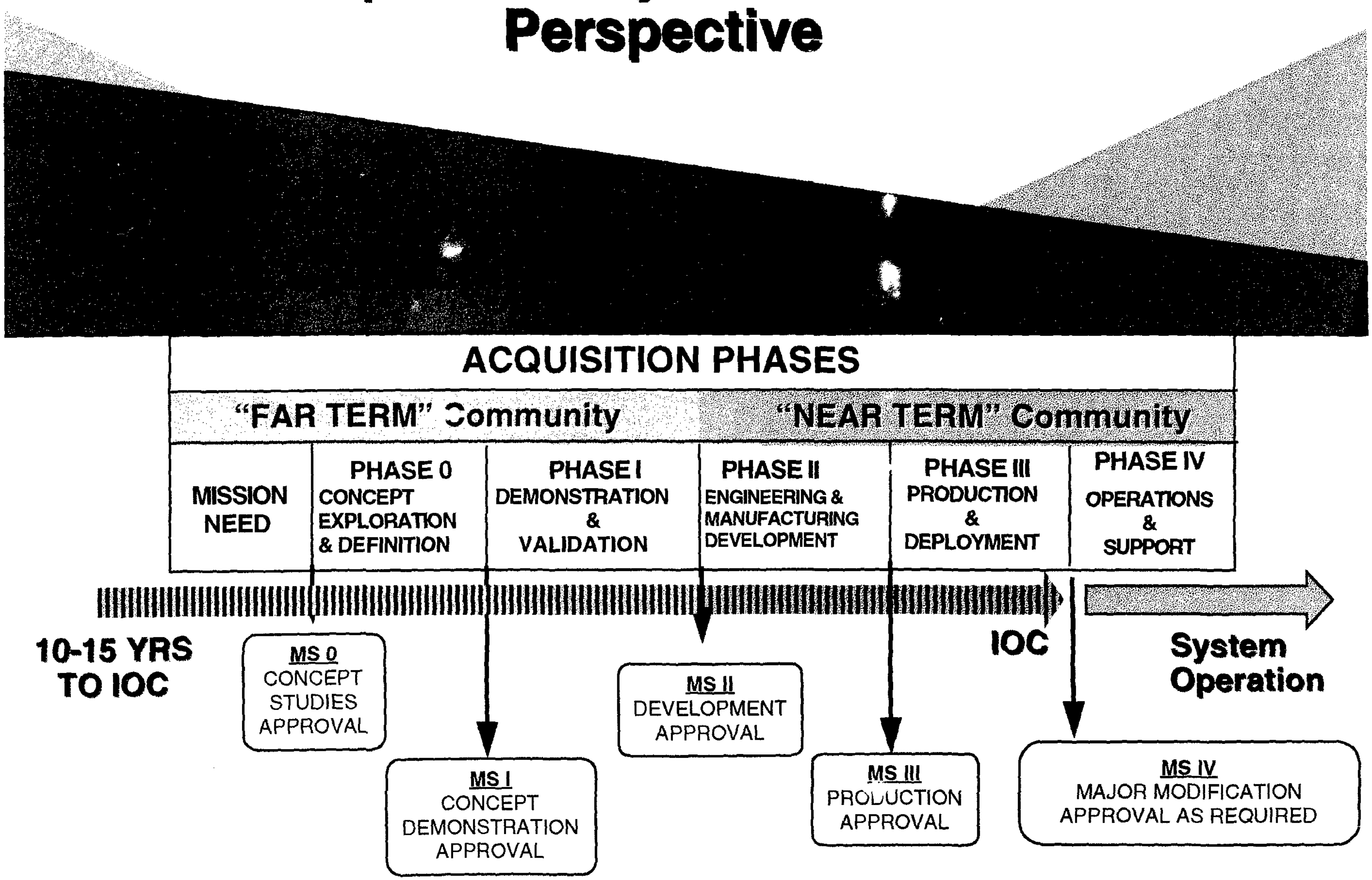
(Are current initiatives such as HLA, J-MASS, DIME, etc. supporting Integrated Assesments?)

- **Several participants expressed concern that funding for architecture development (JMASS/HLA) is taking precedence over fixing model credibility problems**
- **J-MASS not seen as supporting immediate needs of "Far Term" Community**
  - Current focus is on high fidelity models to support Near Term issues (e.g., B-1 DSUP)
- **JTCG/AS seen as needing to take a leadership role in introducing survivability requirements into these overarching initiatives**
  - Requires participation from all concerned: Customers, modelers, analysts, operators, testers ...

SHORTFALLS
(NEAR TERM USERS)

- **Across-the-board concern with credibility of models and analysis at the engagement level (current threat systems)**
  - ECM effects models
  - Blue system models
  - Threat models
  - Threat Missile Endgame models (Pk)

The Acquisition Cycle from the Threat Perspective



SHORTFALLS
(FAR TERM USERS)

- **Requirement for "Iterative Analysis Process"**
  - Due to uncertainties in future scenarios, threats, system capabilities
    - » Need a process for adding new threat technology or technology effects into models
    - » "Authoritative threat databases" are inadequate for long term design leads
  - Requirement for parametric sensistivity analysis
    - » Must evaluate design sensitivity to assumptions about unknowns
    - » "ECM Robustness Analysis" is one example
- **Difficulty conducting credible risk and cost trade-off studies**
  - Need "U.S. System vs. Threat System" at the mission level
    - » Required for cost benefit analysis (CAIV)
    - » IADS and C4ISR modeling particularly important

GENERAL ISSUES

- **Argument over focus: M&S Technology vice Analysis Requirements**
  - Credibility of engagement level simulations seen as taking a back seat to HLA compliance
  - Participants concerned that resources needed to improve analysis capability are focused on other M&S inititatives
  - Cost implications of re-writing existing M&S tools in JMASS architecture an issue
- **Concern that M&S results are seen as "the answer"**
  - M&S are one tool out of many that provide information to analysts
  - Analysts cannot be viewed as "data entry clerks" once authoritative databases and models developed

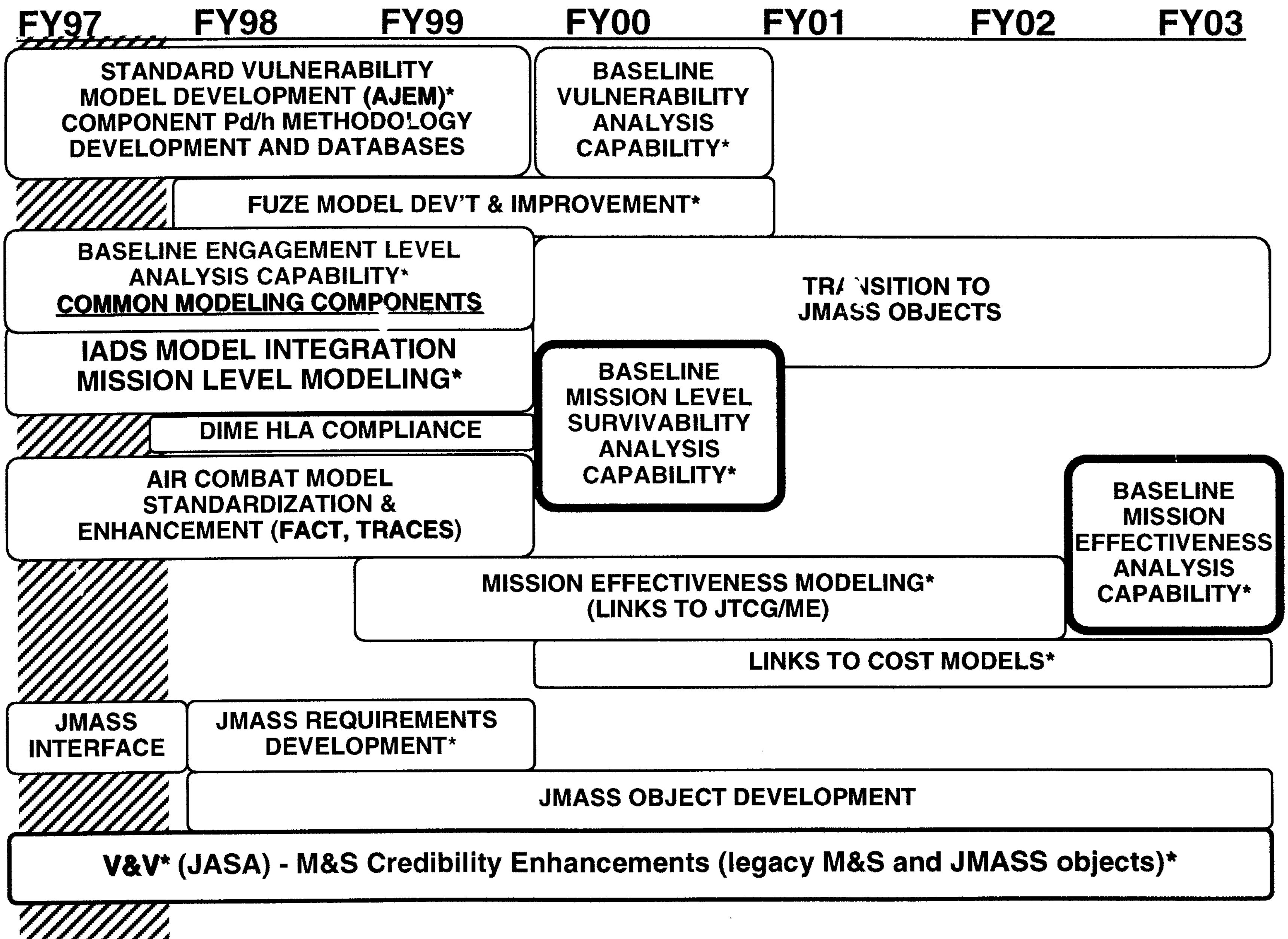
WORKSHOP IMPLICATIONS FOR JTCG/AS

- **MORE EMPHASIS ON M&S CREDIBILITY**
  - Particular y at the engagement level
  - Requirements for missile endgame improvements
- **NEED FOR MISSION LEVEL ANALYSIS CAPABILITY**
  - More emphasis on modeling of IADS
  - **LINKAGES TO COST MODELING**
- **REQUIREMENTS FOR MISSION EFFECTIVENESS MODELING**
  - Survivability as an element of military worth
  - Closer ties with JTCG/ME
  - FY98 Workshop
- **JTCG/AS SHOULD TAKE ON A "LEADERSHIP ROLE" IN DEFINING JMASS REQUIREMENTS**
  - Implications for long term SURVIAC role as well

"PK DAY"

- **Held in conjunction with the Integrated Survivability Assessment Workshop**
- **Objectives:**
  - Initiate joint service approach to Pk analysis methodology in support of EW assesment
    - Net Reduction in Lethality (NRL) vs Reduction In Lethality (RIL)
- **Issues Identified:**
  - Near Field Signature Prediction
    - For fuzing, terminal guidance (miss distance)
  - Continuous Rod Warheads
  - Standardized PK Codes
- **Provides direction for AJEM development**

JTCG/AS METHODOLOGY ROADMAP



* Identified at ISA workshop

SUMMARY

- **INTEGRATED SURVIVABILITY ASSESSMENT IS CRITICAL**
  - To cost-effective aircraft system design, T&E
- **JTCG/AS WORKSHOP IDENTIFIED USER REQUIREMENTS**
  - Future workshops will work on implementation details
- **JTCG/AS ROADMAP WILL ESTABLISH STANDARD, ACCEPTED, JOINT SERVICE TOOLS AND PROCESS**
  - Leveraging service efforts
- **WE NEED PARTICIPATION FROM OSD, THE SERVICES AND INDUSTRY TO MAKE IT WORK**
  - Workshop participation, funding participation

Backup slides

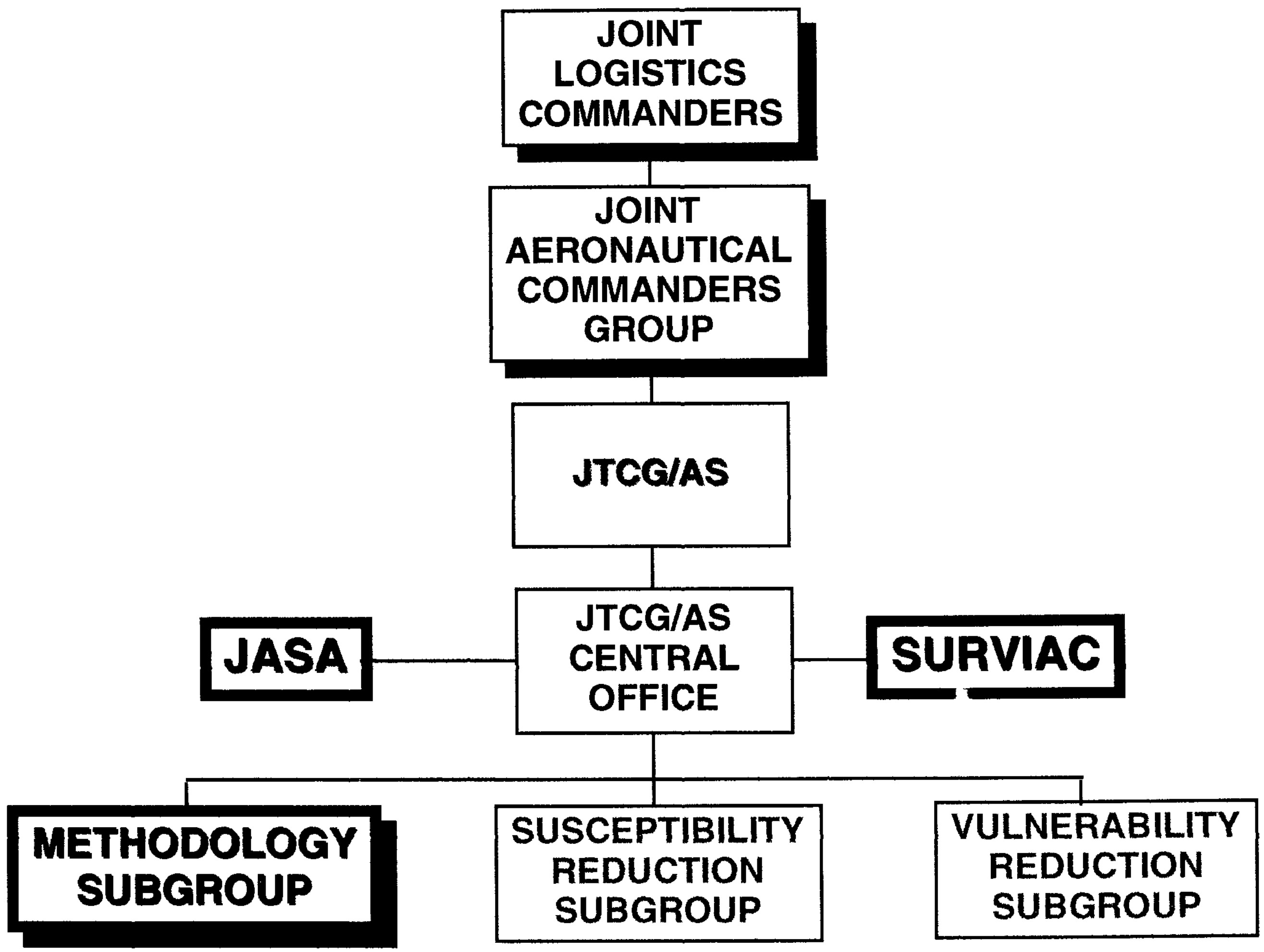
WHAT IS THE JTCG/AS?

- **Joint Technical Coordinating Group on Aircraft Survivability**

- **Chartered by the Joint Aeronautical Commanders Group (JACG) to increase the survivability of aeronautical systems in a nonnuclear threat environment**
  - Coordinate inter-service exchange of information
  - Implement efforts to complement Service survivability programs
  - Ensure availability of aircraft survivability R&D, analytical methodologies and systems criteria

- **JTCG/AS Methodology Subgroup Vision:**
  - Establish an <u>accepted Joint Service Methodology</u> for conducting air weapon system survivability analysis using a <u>flexible and efficient computational environment</u> based on a set of <u>credible modeling components</u>

ORGANIZATIONAL RELATIONSHIPS



JTCG/AS M&S REQUIREMENTS

- **TRI-SERVICE ACCEPTED M&S FOR SURVIVABILITY ANALYSIS**
  - Accepted by the community
  - Configuration Managed
  - Meeting a V&V standard

- **COORDINATED DEVELOPMENT**
  - Leveraging service M&S initiatives for multi-service use

- **AVAILABLE TO THE TRI-SERVICE ACQUISITION COMMUNITY**
  - Documented
  - Distributed through SURVIAC

WHAT IS SURVIAC?

- **Survivability/Vulnerability Information Analysis Center**
  - Chartered under the JTCG/AS and JTCG/ME
  - Funded by DLA

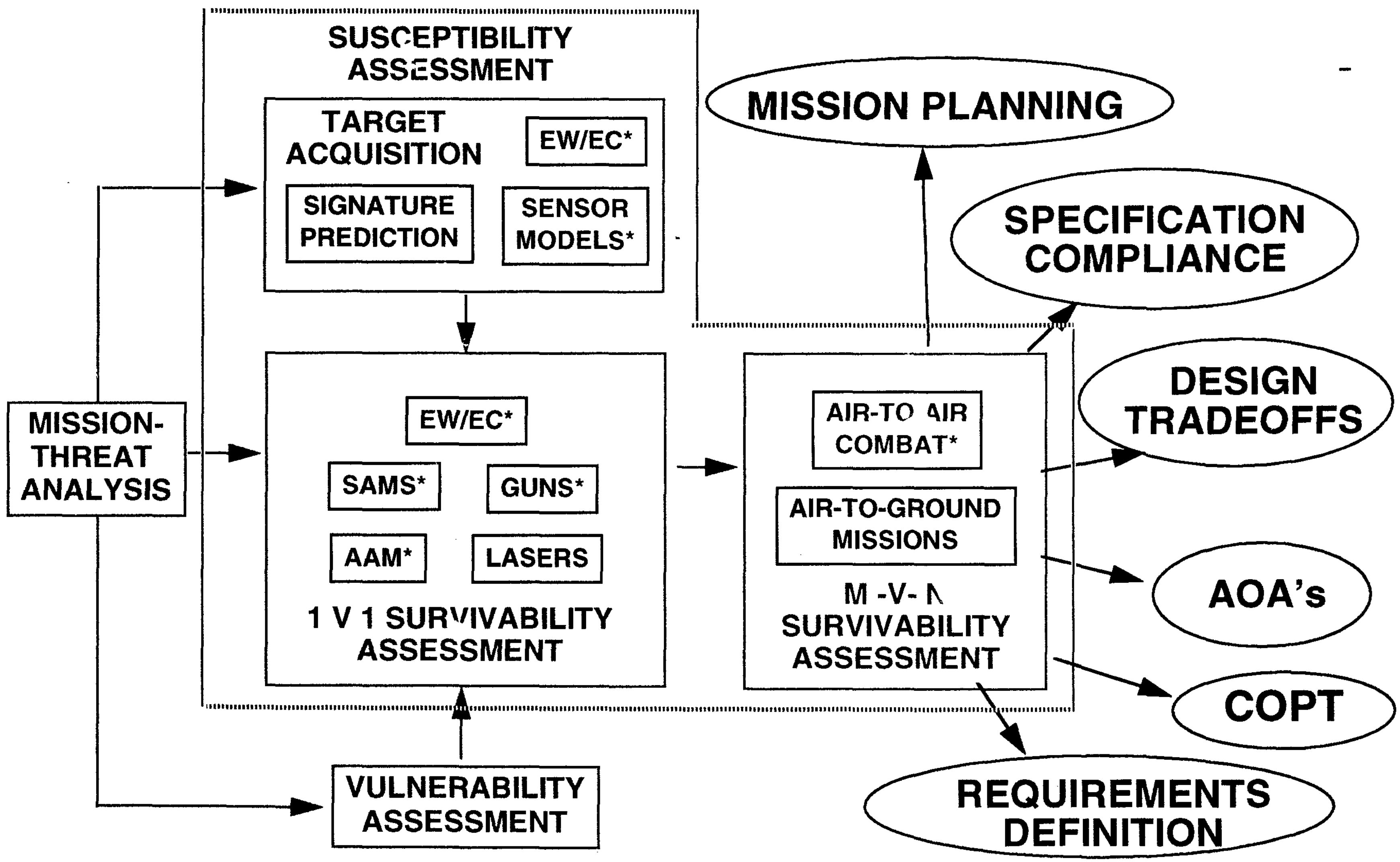
- **Provides data, standard methodologies and analysis in support of system survivability and lethality**
  - Combat survivability data base
  - Workshops, training
  - Model and simulation repository & distribution

- **Model entry into SURVIAC constitutes tri-service endorsement**
  - JTCG/AS and/or JTCG/ME

WHAT IS JASA?

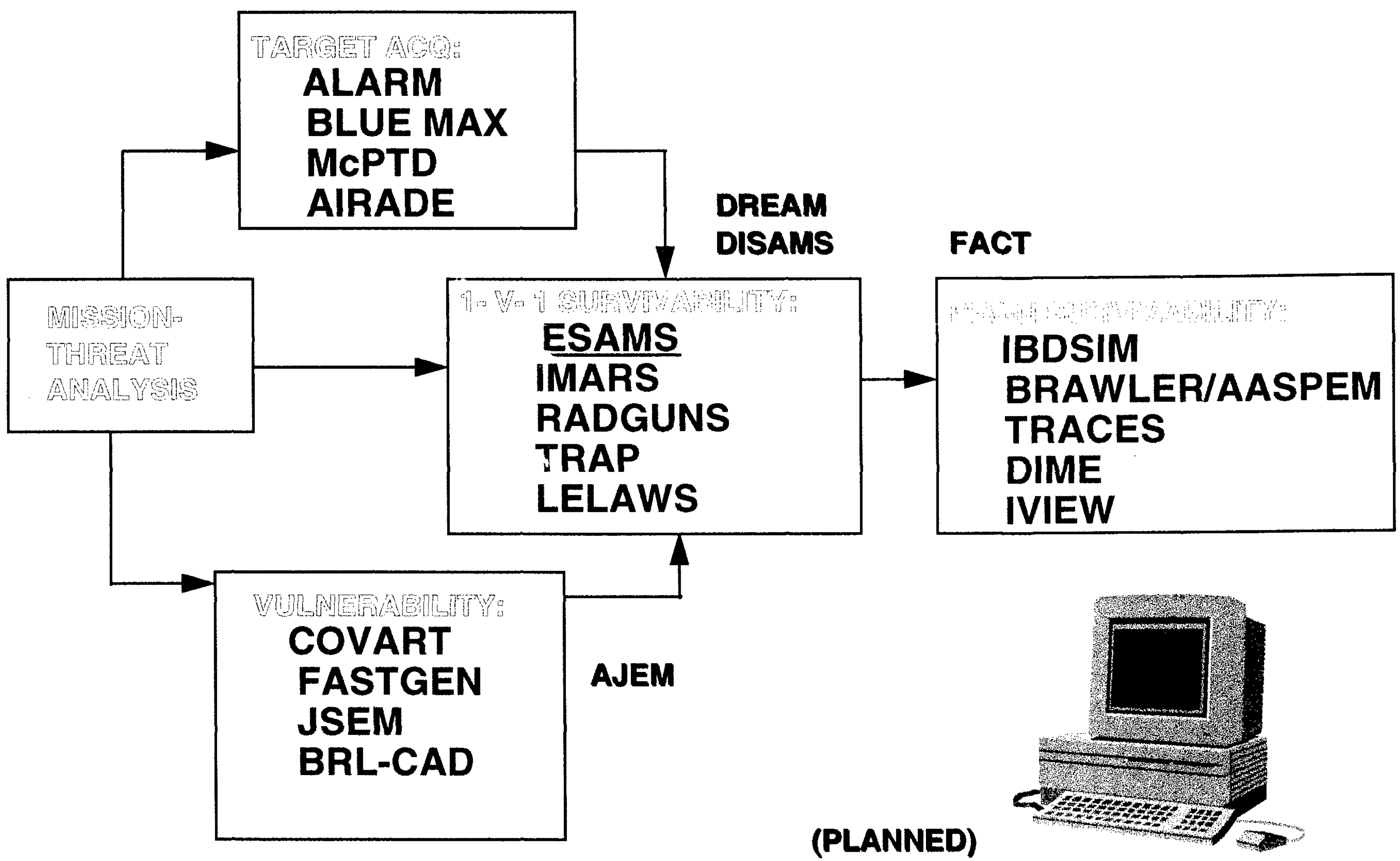
- **JOINT ACCREDITATION SUPPORT ACTIVITY**
- **Provides Model and Simulation (M&S) Verification, Validation and Accreditation (VV&A) Support**
  - To acquisition programs (and anyone else who needs help)
  - JTCG/AS Central Office serves as central Washington, D.C. POC and provides coordination with customers
  - Technical services provided through program office at NAWCWPNS
- **A response to stated customer requirements for continued VV&A support from a joint activity**
  - Builds on customer base from the SMART project

THE SURVIVABILITY ASSESSMENT PROCESS

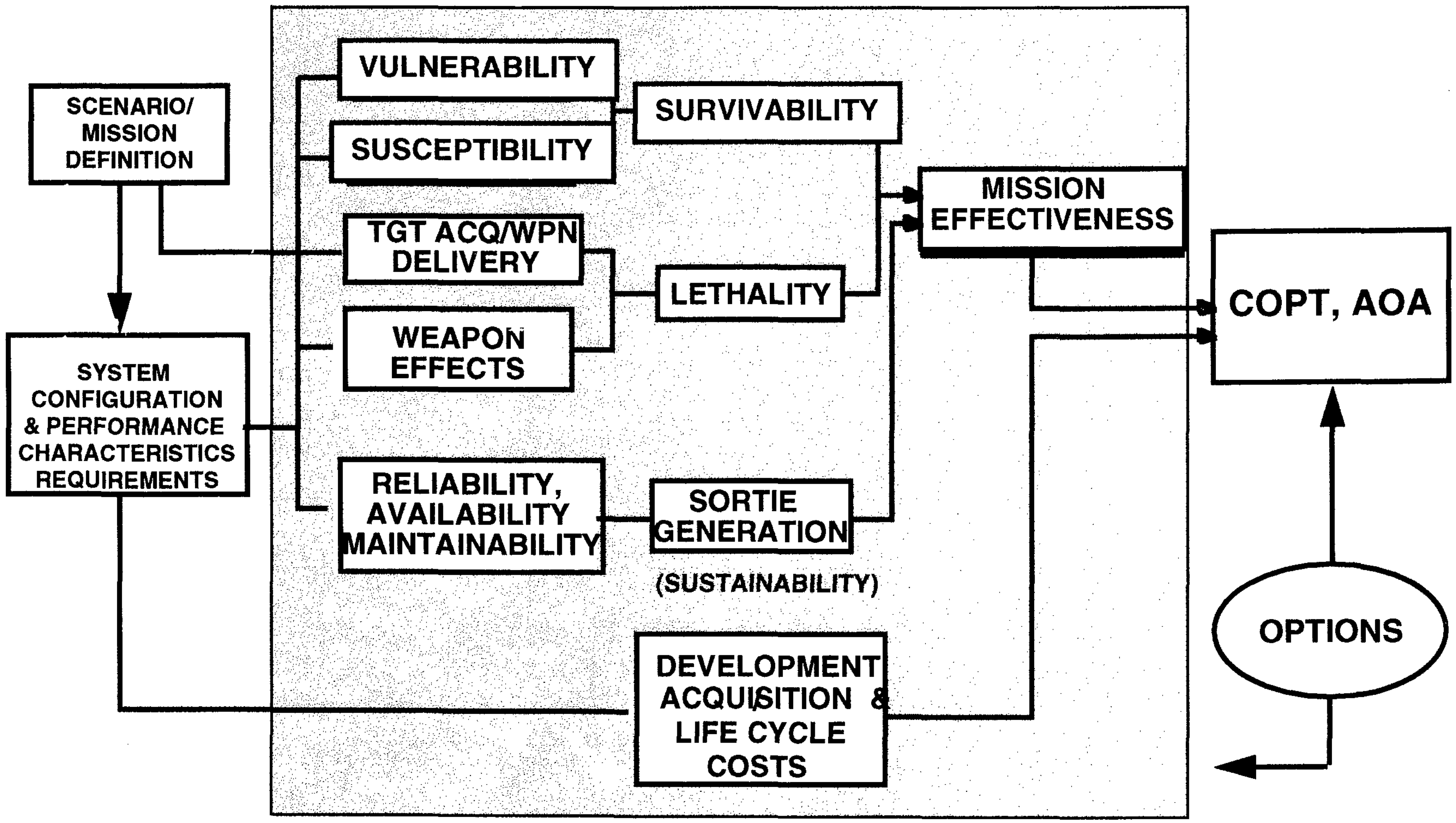


* ADDRESSED BY SMART

CURRENT JTCG/AS MODELS IN THE ASSESSMENT PROCESS (IN SURVIAC)



RELATIONSHIP TO MISSION EFFECTIVENESS



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BALANCING SURVIVABILITY ATTRIBUTES: THE COST OF MISSION SUCCESS

ALEX LOEWENTHAL, PH.D.
LOCKHEED MARTIN SKUNK WORKS
PALMDALE, CA 93599-2514

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THE COST OF MISSION SUCCESS

- **BALANCING THE SURVIVABILITY ATTRIBUTES**
  - CHALLENGES
  - TOOLS
  - APPLICATIONS
- **VULNERABILITY IN THE BALANCE**
  - NEW PARADIGM
  - ANALYSIS REQUIREMENTS
  - VULNERABILITY ANALYSIS AS A REQUIREMENT SOURCE
- **THE CRITICAL ELEMENT: COST**

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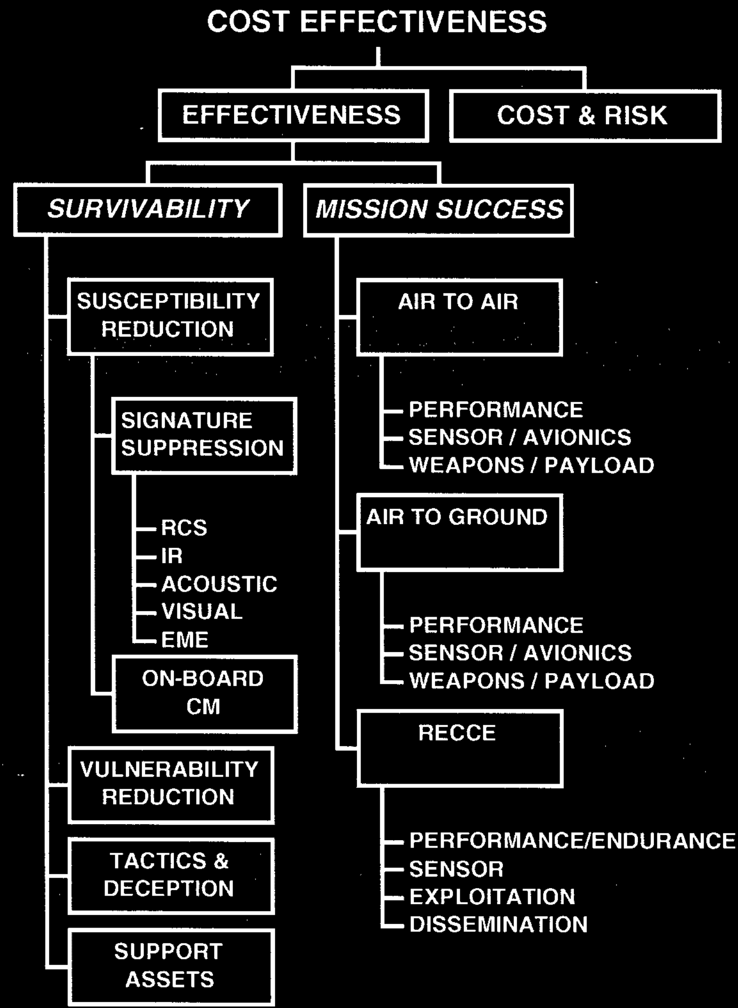
BALANCING WEAPON SYSTEM ATTRIBUTES

EFFECTIVE, AFFORDABLE WEAPON SYSTEMS INCORPORATE ALL THE NECESSARY SURVIVABILITY AND MISSION SUCCESS ATTRIBUTES TO THE EXTENT THAT THEY CONTRIBUTE TO MISSION SUCCESS



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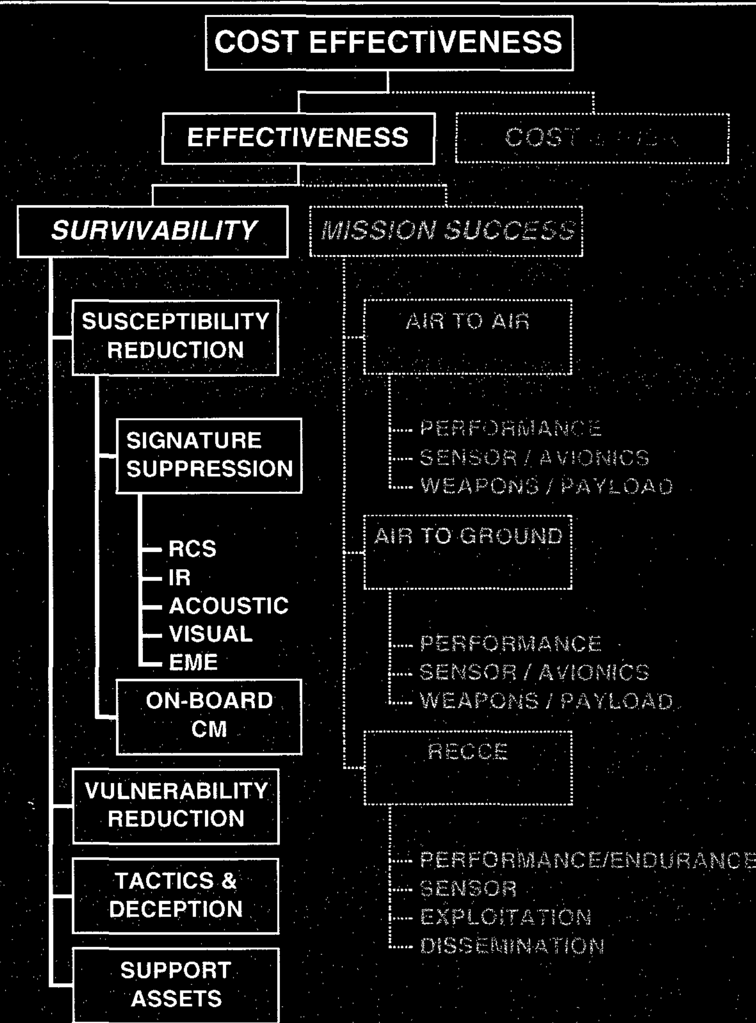
BALANCING SURVIVABILITY ATTRIBUTES

BALANCING ATTRIBUTES WRT

- MISSION NEEDS
- EACH OTHER

TO ACHIEVE LOWEST COST OF MISSION SUCCESS



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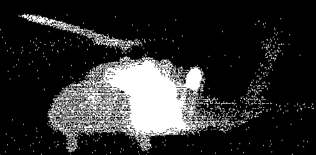
BALANCED IR REQUIREMENTS

- **INCREASING COMPLEXITY OF REQUIREMENTS...**
  - IRCM WAS EFFECTIVE AND WAS CHEAPER THAN SUPPRESSION
  - AVAILABILITY OF IR WEAPONS
  - PROLIFERATIONS OF MISSILE TYPES AND TECHNOLOGIES



... NECESSITATES NEW TECHNIQUES AND METHODOLOGIES
  - SIGNATURE SPECIFICATION TO SURVIVABILITY REQUIREMENT
  - NEW ANALYSIS TOOLS AND IMPROVED OLD ONES
    - **DETAILED IRCM**
    - **EXTENDED SOURCE IMAGE CAPABILITY**
    - **CONSISTANT DATABASES**
  - FLOW UP AND FLOW DOWN OF REQUIREMENTS

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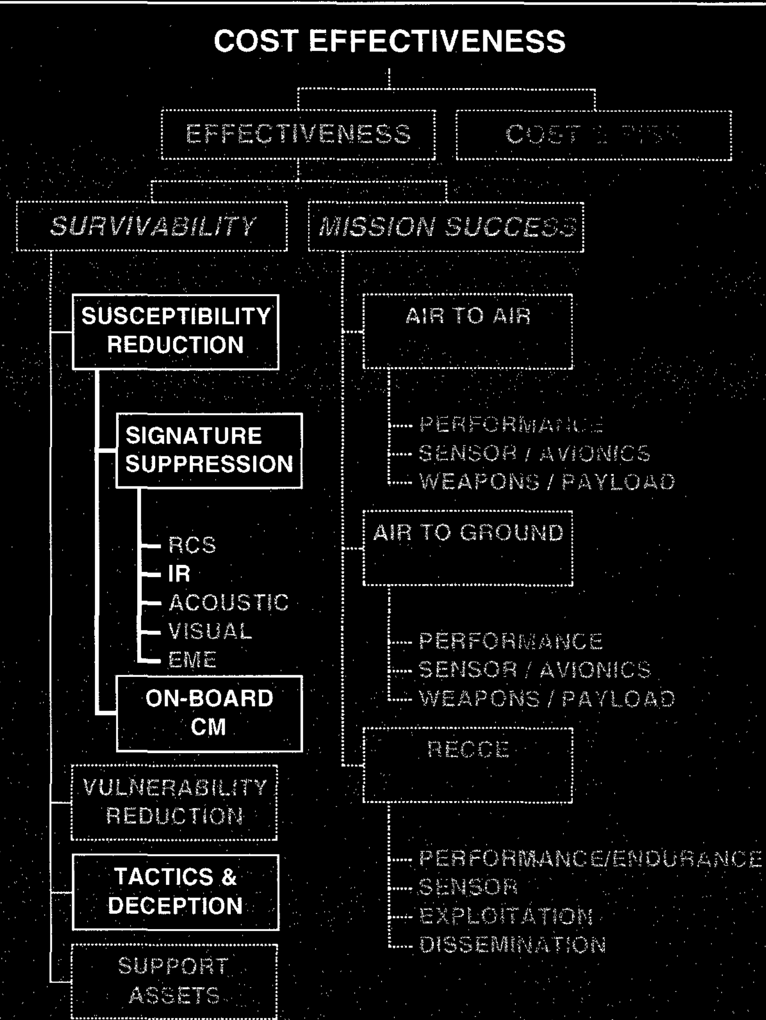
SURVIVABILITY IMPROVEMENTS

- **TRANSPORT AIRCRAFT**
  - IR SIGNATURE REDUCTION
  - IRCM
  - LOW ALTITUDE REGIME



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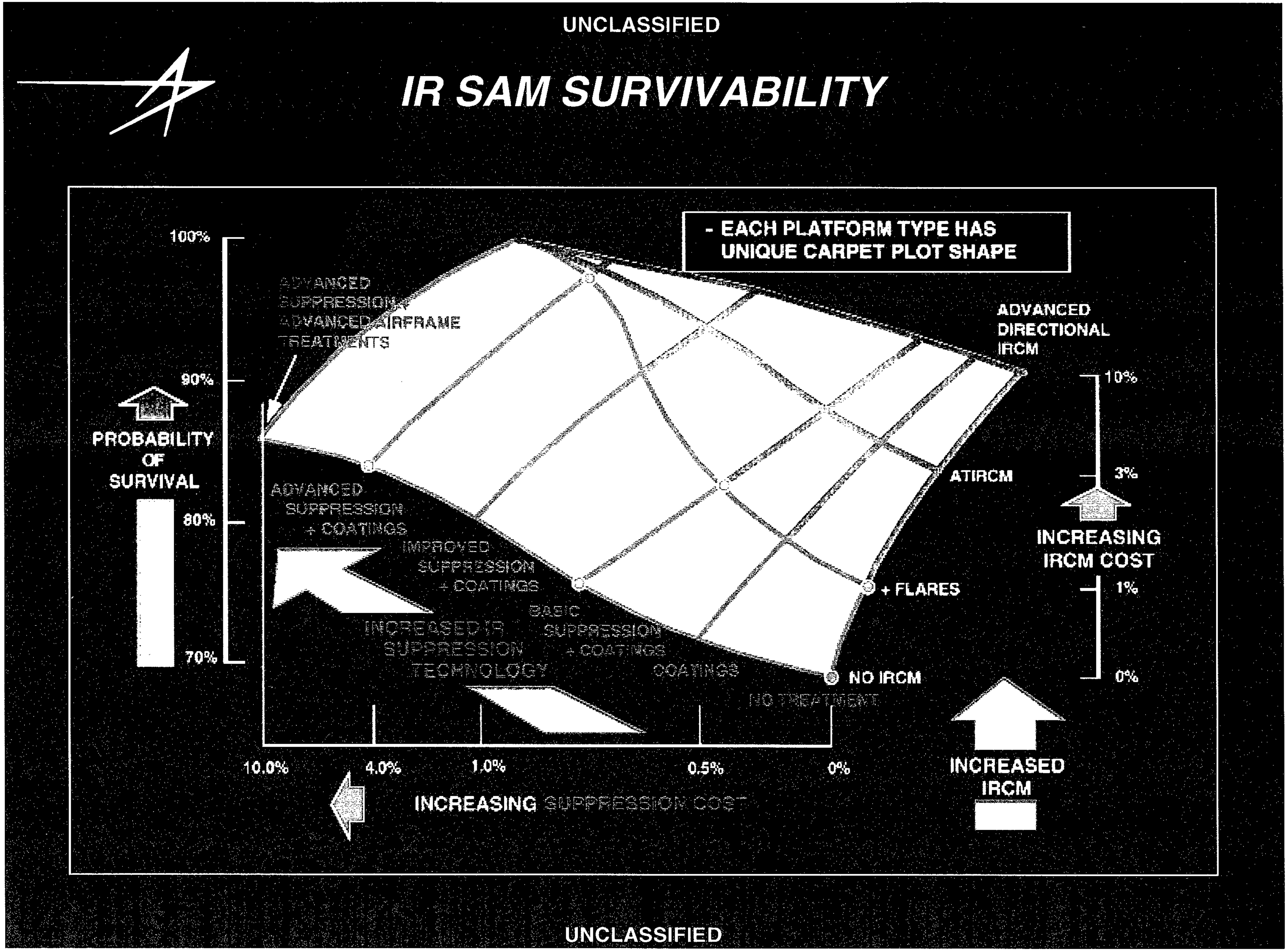
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IR SAM SURVIVABILITY
- EACH PLATFORM TYPE HAS UNIQUE CARPET PLOT SHAPE
100%
90%
80%
70%
PROBABILITY OF SURVIVAL
ADVANCED SUPPRESSION + ADVANCED AIRFRAME TREATMENTS
ADVANCED SUPPRESSION + COATINGS
IMPROVED SUPPRESSION + COATINGS
BASIC SUPPRESSION + COATINGS
COATINGS
NO TREATMENT
INCREASED IR SUPPRESSION TECHNOLOGY
ADVANCED DIRECTIONAL IRCM
ATIRCM
+ FLARES
NO IRCM
10%
3%
1%
0%
INCREASING IRCM COST
INCREASED IRCM
10.0%
4.0%
1.0%
0.5%
0%
INCREASING SUPPRESSION COST
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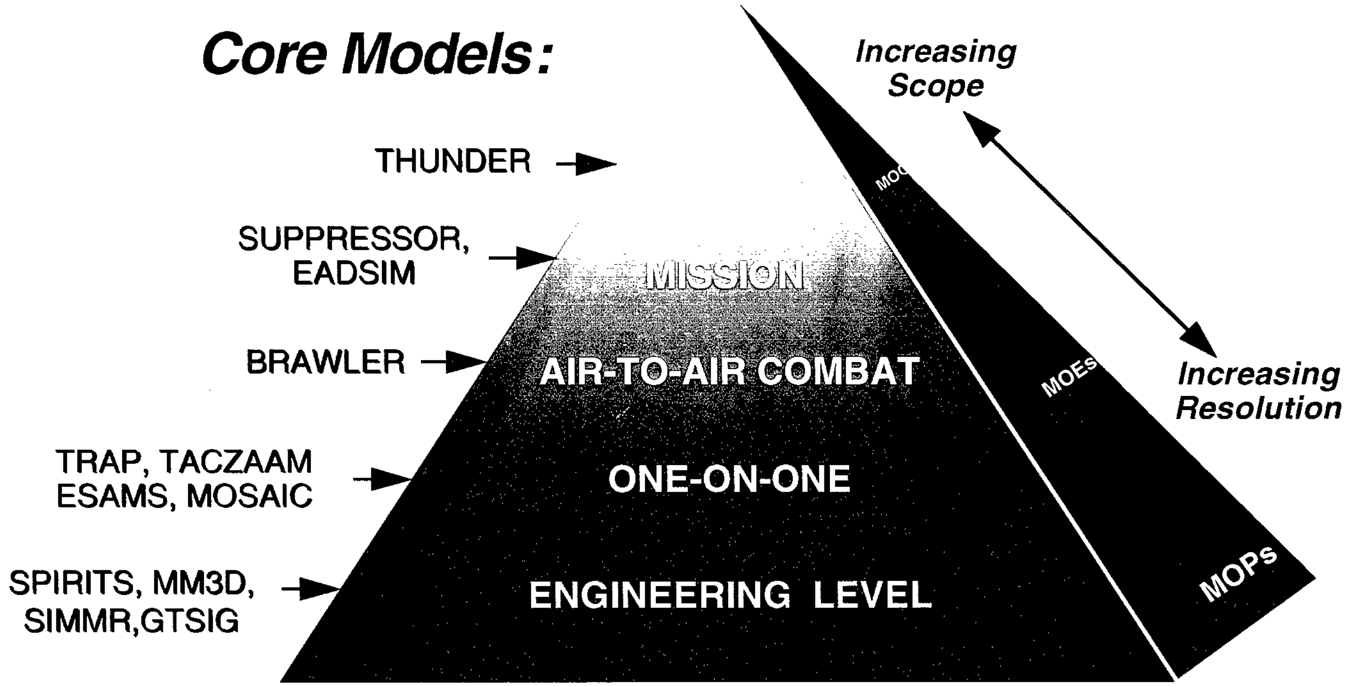
ANALYSIS AND MODEL HIERARCHY

Core Models:



Metrics:
Measures of Outcome (MOOs)
Measures of Effectiveness (MOEs)
Measures of Performance (MOPs)

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MODELING FIDELITY AND COMPUTATIONAL BURDEN

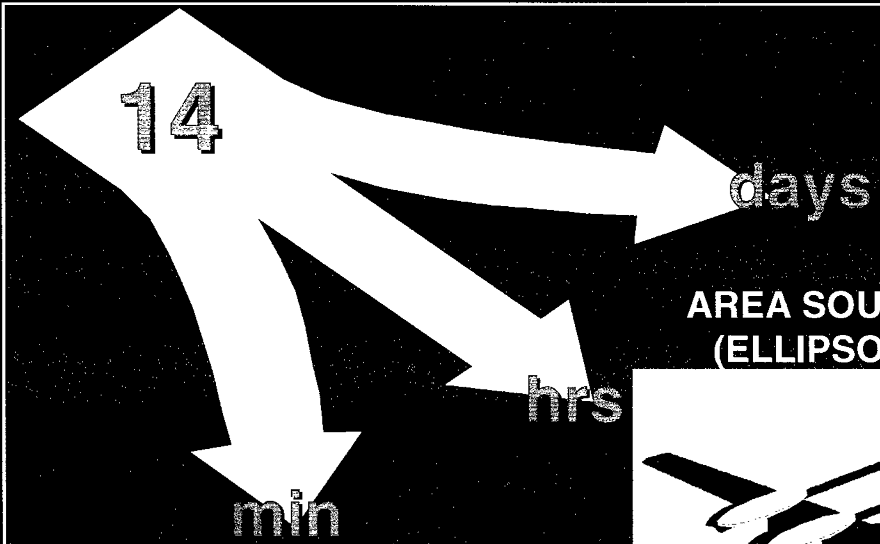
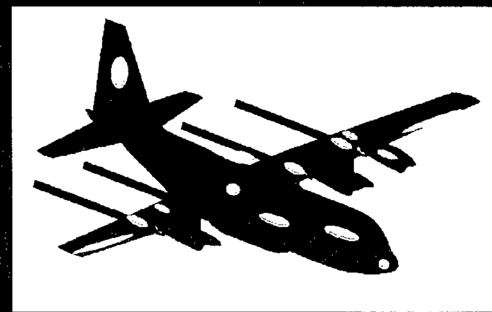


IMAGE SOURCES (GRAPHIC RADIANCE MAPS)

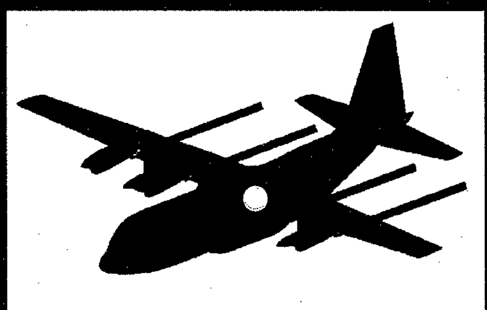


- INDIVIDUAL CONTRIBUTORS
- SEE WHAT MISSILE SEES
- TRUE EXTENDED SOURCES
- EDGES
- MOSAIC 2.0+

AREA SOURCES (ELLIPSOIDS)

- WIREFRAME
- MULTIPLE SOURCES
- MOSAIC 1.4 or 2.0

POINT SOURCE



- QUICK & EASY

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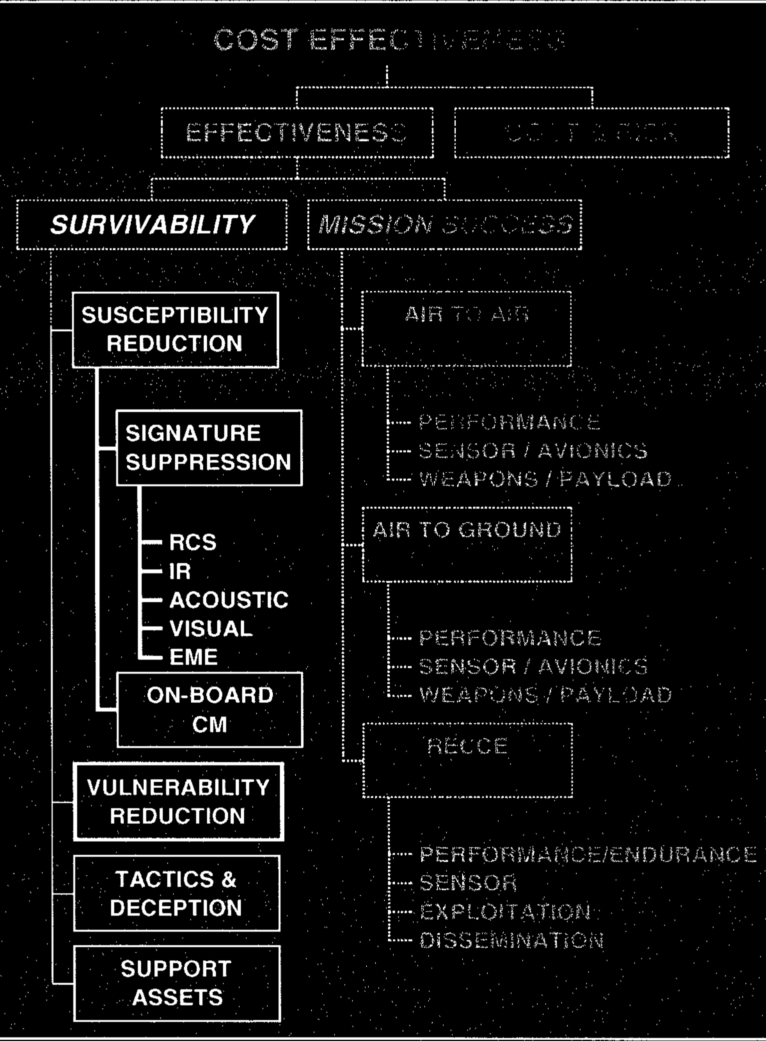
VULNERABILITY REDUCTION

- **TRADITIONAL OBJECTIVES**
  - MAXIMUM HARDENING WRT AAA THREAT
    - **PROVIDES HARDNESS TO ALL THREATS**
  - NO OR MINIMUM IMPACT ON COST, PERFORMANCE, WEIGHT
  - PROVIDE GUIDANCE IN AIRCRAFT DESIGN
- **REFINED OBJECTIVES**
  - TRADE OFF HARDENING WITH DIMINISHED THREAT EFFECTS DUE TO CM



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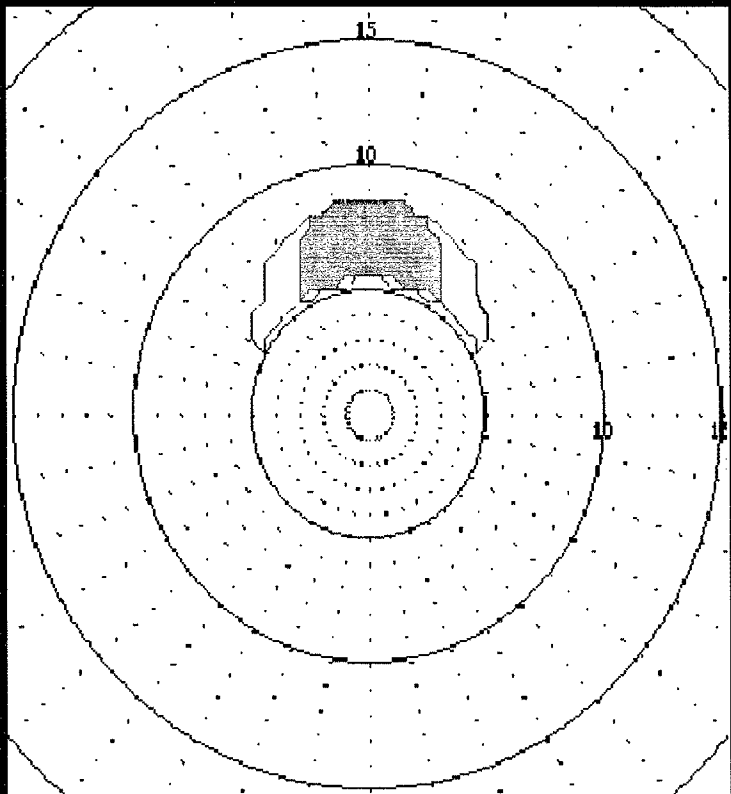
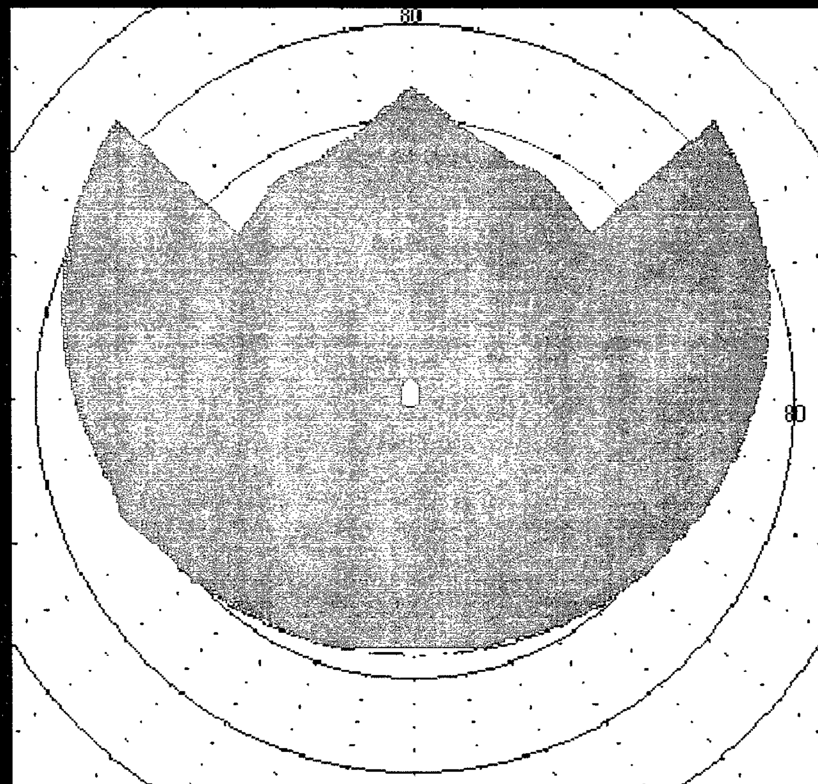
TRADITIONAL VULNERABILITY REDUCTION OBJECTIVES FALL SHORT





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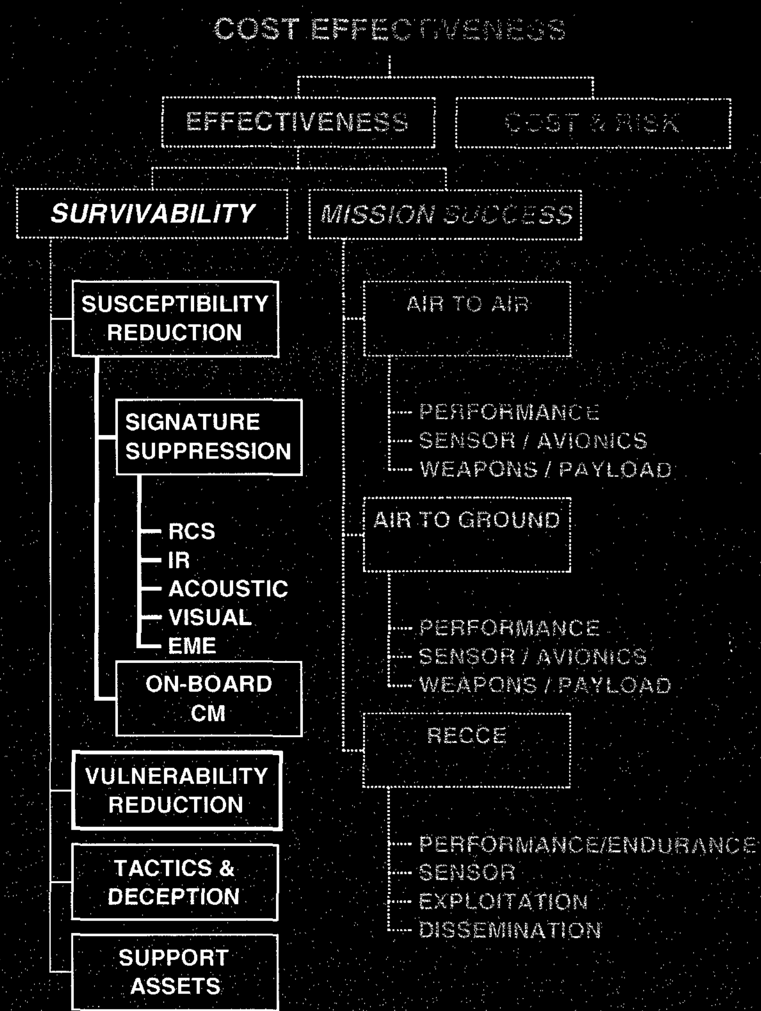

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VULNERABILITY REDUCTION IN BALANCED SURVIVABILITY

- **DEVELOP A SANCTIONED WARHEAD LETHAL RADIUS METHODOLOGY**
- **CONSIDER THREATS LIKELY TO BE ENCOUNTERED**
  - NOT 23MM HEI PROJECTILE AGAINST AN A/C AT 50 KFT
- **UNDERSTAND DAMAGE EFFECTS FROM WARHEAD DETONATION AT APPROPRIATE DISTANCES**
  - FRAGMENTS AS KILLERS OF STRUCTURE & OF INTERNAL COMPONENTS; FRAGMENTS AS FIRE INITIATORS; BLAST EFFECTS ON STRUCTURE

WARHEAD LETHAL RADIUS INCONSISTENCIES

	Weight	Charge	Frag	Frag Vo	Frag #	Angle	Radius	KJ/ft^2
H	73	36.3	1.94	1900	16700	75	21.9	0.7
P	73	30	1.94	1900	21480	90	27.4	0.4
3	73	40.6	4.67	2240	4530	41	11.0	7.5
5	217	90	2/3.5 g	1200 / 1800	16000 / 21000	120	25.0	0.8
2	192	121	7.06	2800	8000	15	29.9	7.0
1	130	75	2.5	2700	22000	30	30.5	2.2

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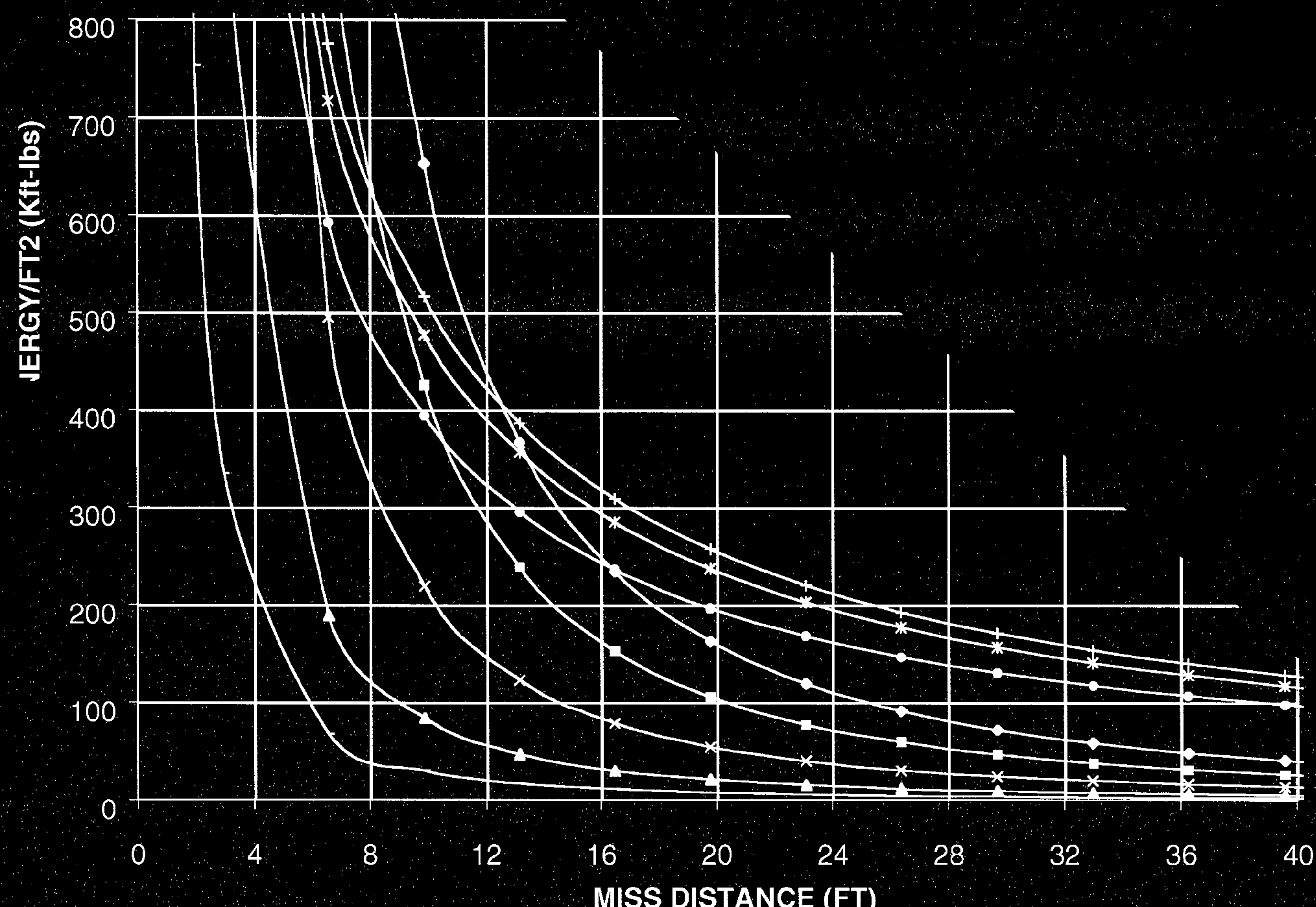
THREAT ENERGY PER UNIT AREA VS MISS DISTANCE



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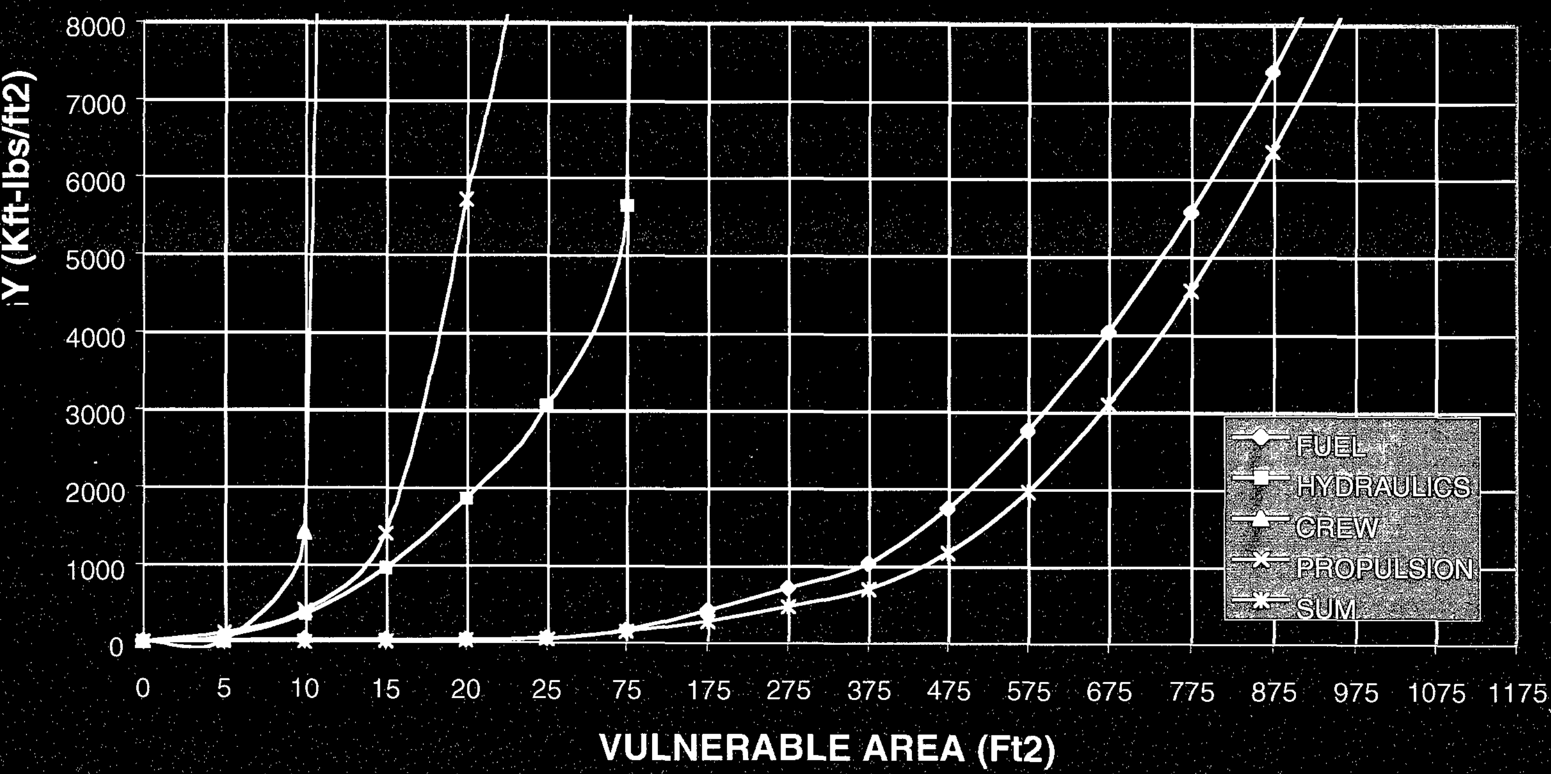
THREAT ENERGY VS VULNERABLE AREA



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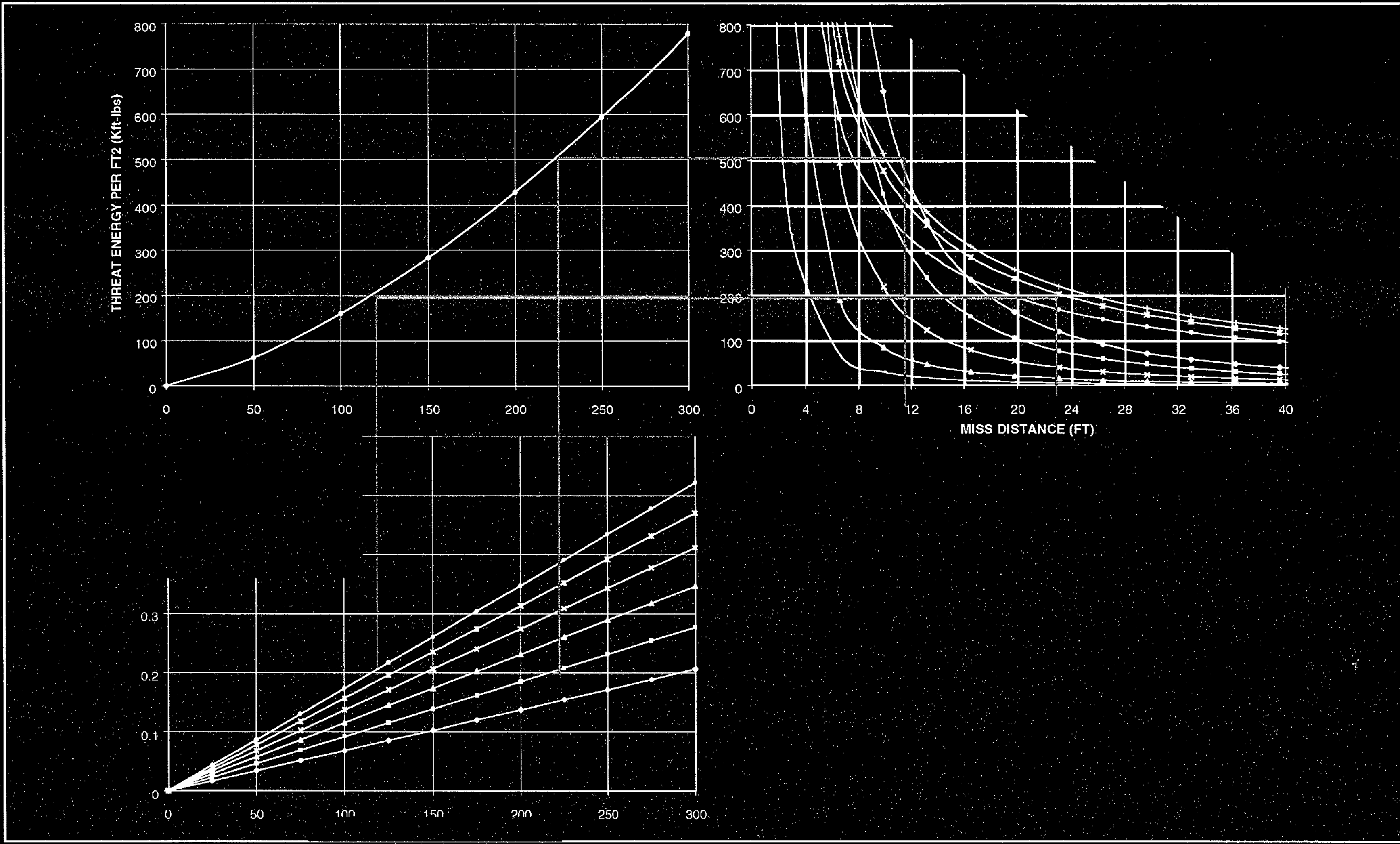
WARHEAD LETHAL RADIUS NOMOGRAPH



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THE CRITICAL ELEMENT: COST

- **PRESENTED IN VARIOUS FORMS TO ADDRESS FINANCIAL AND SUBJECTIVE ISSUES**
  - FLY-AWAY COST - OUT OF POCKET...
  - LIFE CYCLE COST - IN THE LONG RUN...
  - CAIV - WHAT CAN I BUY FOR...
  - AFFORDABILITY - ...

THE CRITICAL ELEMENT: COST

- COST OF MISSION SUCCESS (AND FAILURE) IS A FUNCTION OF PRIORITIES, STRATEGY, NATIONAL RESOLVE
  - APOLLO
  - MANHATTAN PROJECT
  - ...
- WEAPON SYSTEM COST MUST BE CONSIDERED IN THE CONTEXT OF MISSION SUCCESS.

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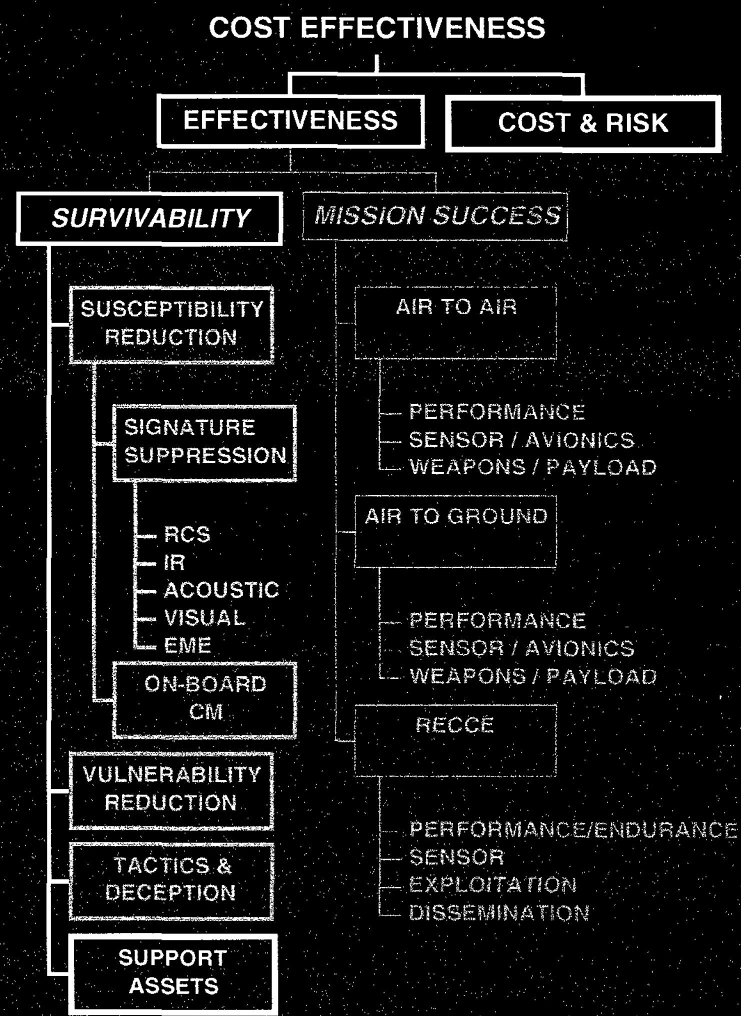
THE CRITICAL ELEMENT: COST

- **RELIANCE ON EXTERNAL SYSTEMS FOR SURVIVABILITY , COMMITS THE USER TO MAINTAIN / UPGRADE / REPLACE THE SUPPORT ASSETS IN INVENTORY.**
  - CRUISE MISSILE STRIKES & SEAD
  - HIGHLY SURVIVABLE AIR-TO-GROUND SYSTEMS
  - HIGHLY SURVIVABLE AIR-TO-AIR SYSTEMS
  - STAND-OFF JAMMERS
  - TANKERS



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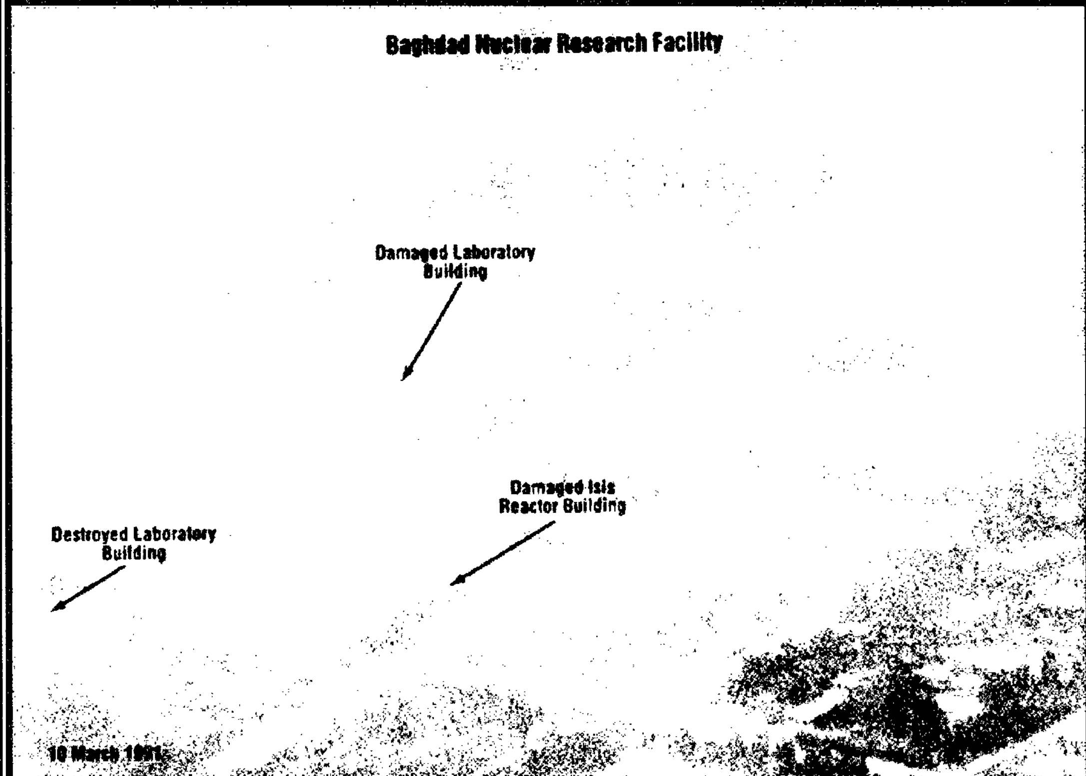
COST OF MISSION SUCCESS



STRIKE	32	8
F-15	16	
EF-111	4	
F-4G	8	
TANKER	15	2
AIRCRAFT	75	10
LOSSES	2	0
AIRCREW	72 - 132	8 - 16
ASSETS	$2,328M	$597M
SORTIE COST	$7,949K	$956K
ACQ.	$9,073M	$1,756M

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THE COST OF MISSION SUCCESS

- **ONLY WEAPON SYSTEMS THAT ARE, IN THEMSELVES, SURVIVABLE AND EFFECTIVE OFFER THE PROMISE OF LOW COST IN MISSION SUCCESS.**
  - THEY ALSO HAVE THE POTENTIAL TO REDUCE THE TOTAL WEAPONS SYSTEM INVENTORY.

- **MOE'S MUST REFLECT THE CONTRIBUTION OF ALL SYSTEMS BROUGHT TO BEAR IN A MISSION.**
  - COST AND BENEFIT

Flight Systems' Integration Impact On Aircraft Vulnerability

Bruce Clough

JTCG/AS Vulnerability Reduction Subgroup, Flight Systems Committee

John Perdzock

Flight Control Division

Air Force Research Laboratory

Technical Content Meter:

Low **High**

JTCG/AS

Purpose & Overview

- Sensitize Survivability Personnel To Technological Advances In Flight Systems
    - What are the new technologies?
    - How do they impact vehicle vulnerability?
    - Do we need to "worry"?
    - ...if so, what should we do?
- What will be covered
    - Short Review Of Each Technology
    - Possible Vulnerability Impacts
    - Where To Go From Here

Technology Areas Covered

- Integrated Flight/Propulsion Control
- Tailless Aircraft
- Integrated Flight/Structure Control
- More Electric Aircraft
- Integrated Thermal/Secondary Power
- Prognostics & Health Management
- Vehicle Management Systems

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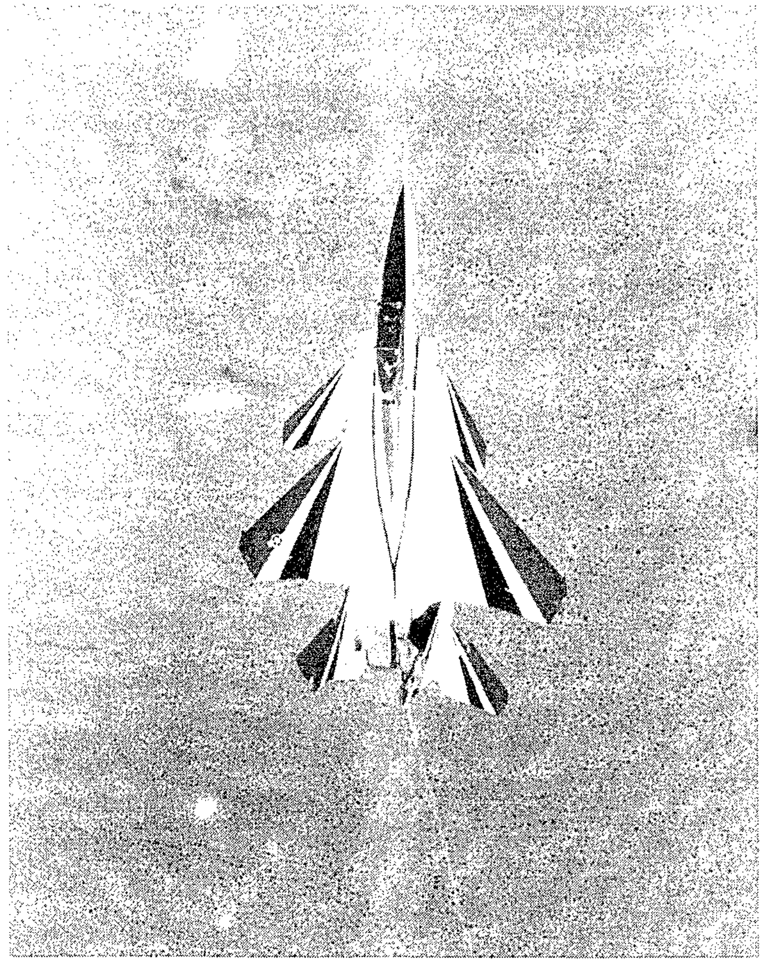
Integrated Flight/Propulsion Control

- IFPC Integrates Separate Flight and Engine Control Functions
- IFPC Empowers Greater Aircraft Performance
  - Enhanced Maneuvering
  - Reduced Fuel Consumption
- Plenty Of IFPC System Experience
  - STOL/Maneuver Technology Demonstrator
  - NASA/HARV
  - MATV F-16
  - X-31, et al

...oh, and the F-22...



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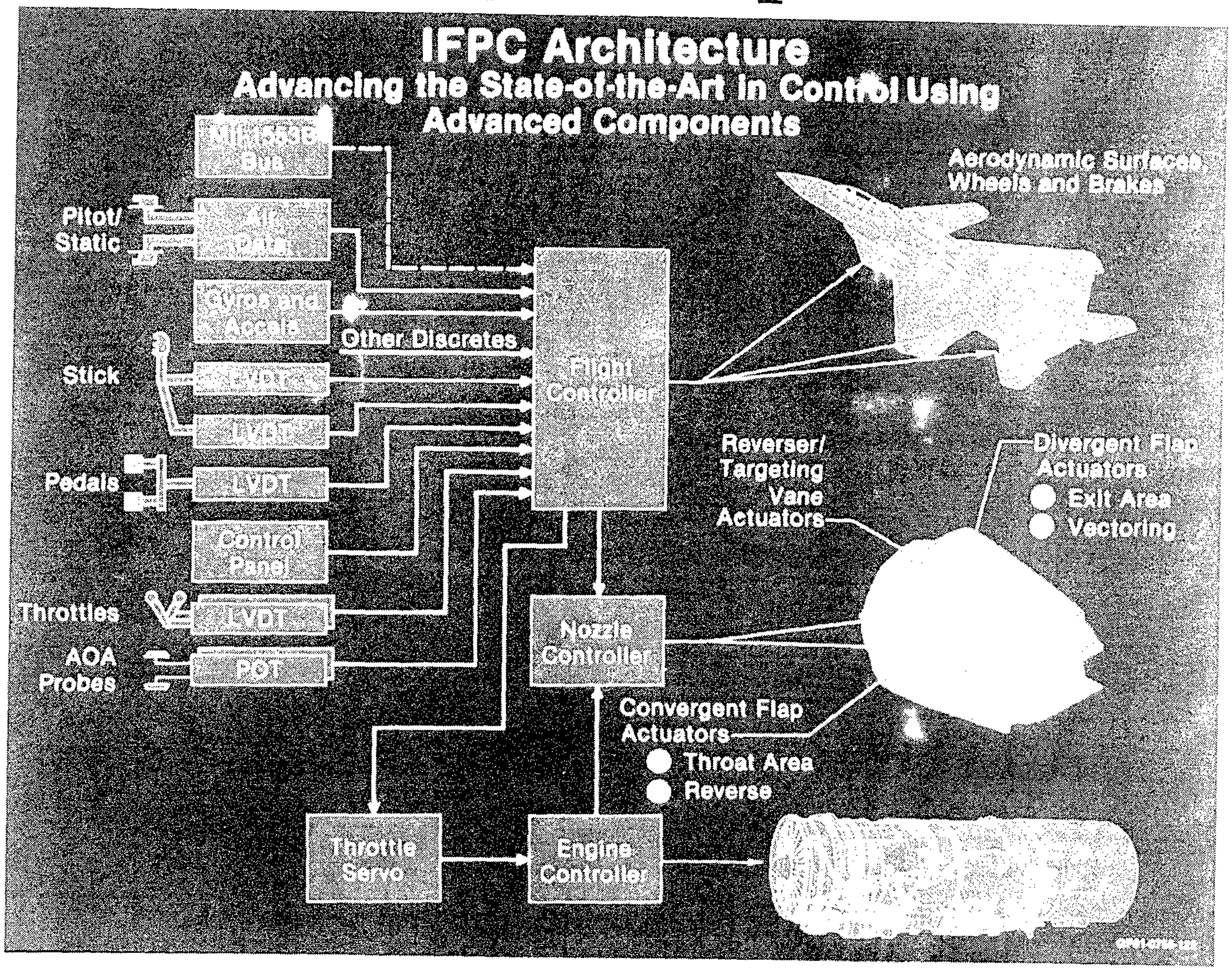
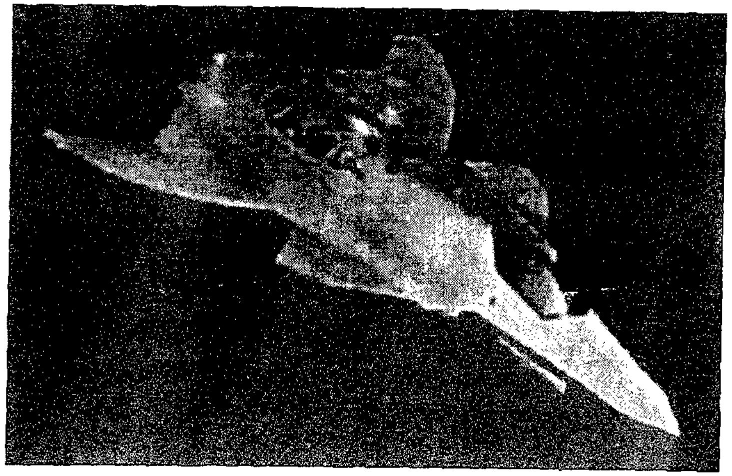
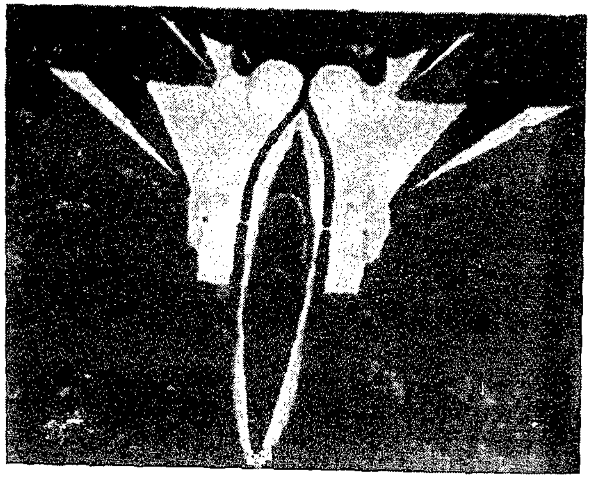
Integrated Flight/Propulsion Control



Tailless Fighter Aircraft

Highly maneuverable tactical aircraft…





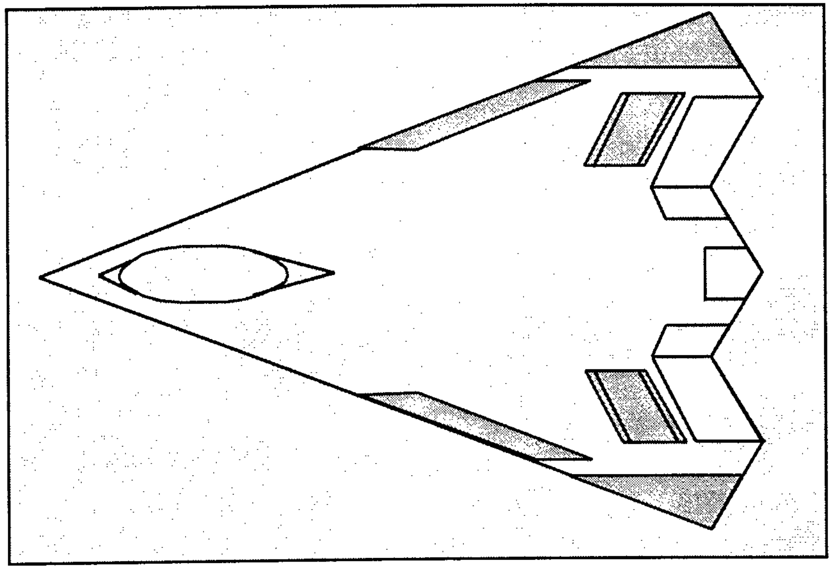
…with reduced or *no vertical tail*

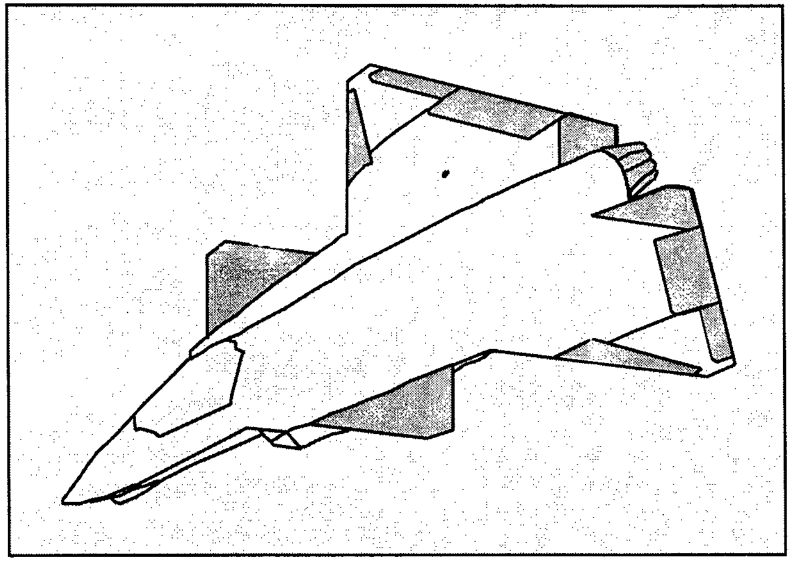
Benefits:
- Lower observability
- Reduced weight

Challenges:
- Reduced directional stability
- Reduced directional control power
- Maintain current maneuverability

Tailless Fighter Aircraft

Flight control system restores directional control power...





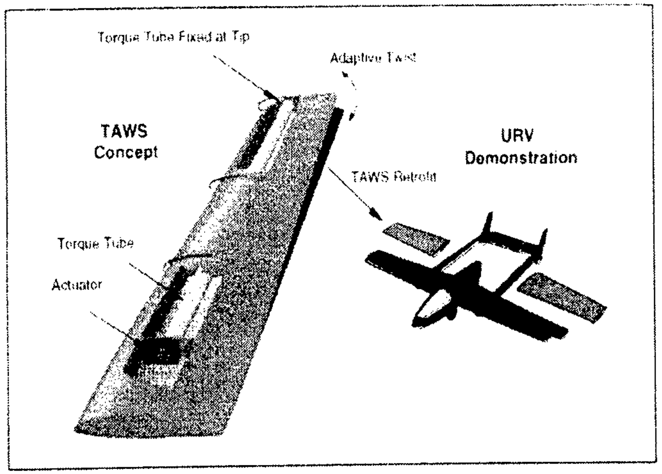
...using innovative control effector suite and advanced control theory

Integrated Flight/Structure Control

- **IFSC is the active, real-time controlling of aircraft structure to:**
  - **Eliminate Structural Weight**
  - **Increase Aircraft Agility**
- **Current Wing Weight Driven By Torsional Stiffness, Not Strength**
- **Using Active Control Allows:**
  - **Structural Load Control (Maneuver, Gust)**
  - **Structural Shape Control (Twist, Camber)**
  - **Structural Mode Control (Vibration, Flutter)**

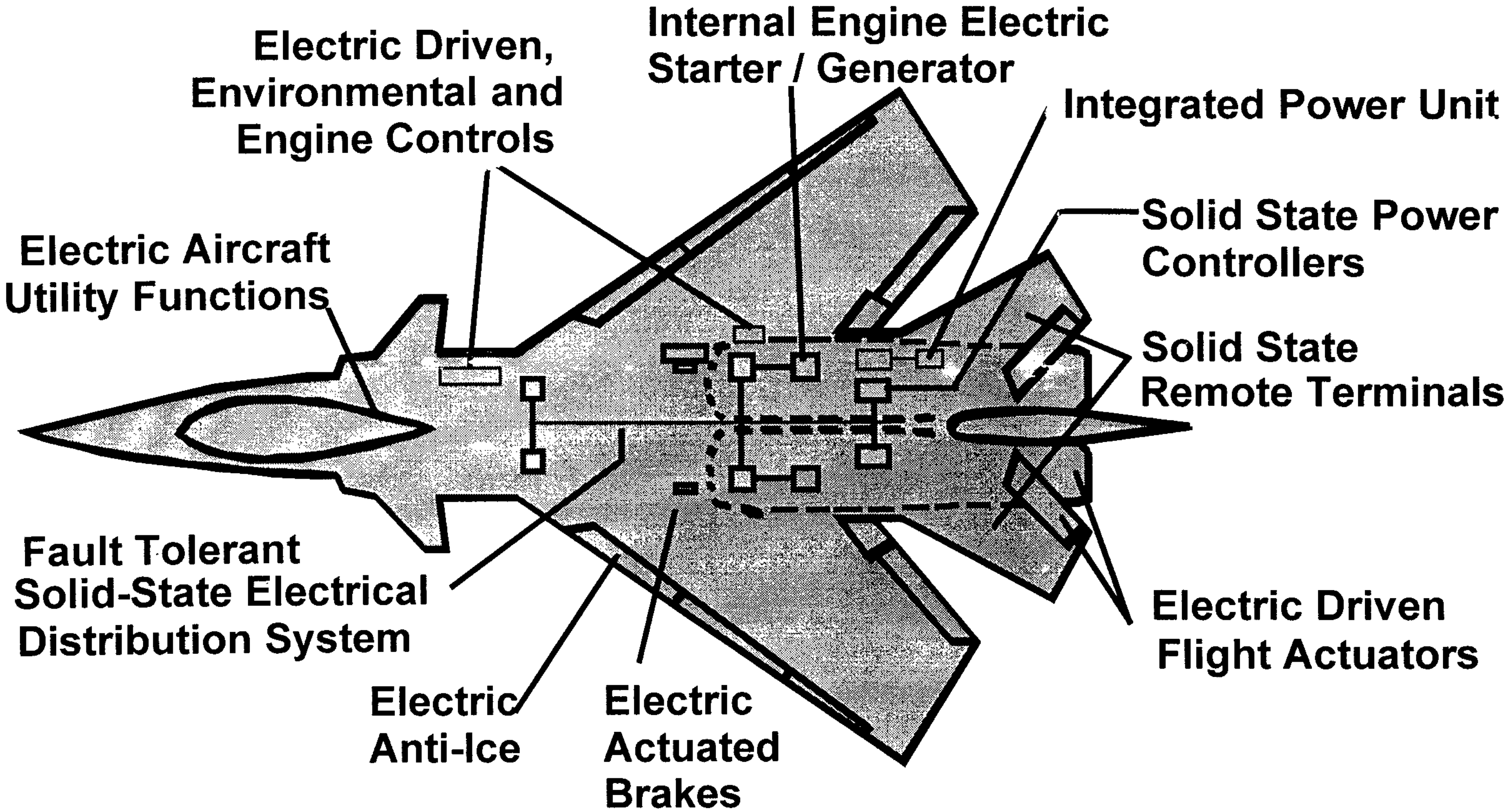
Integrated Flight/Structure Control: Ongoing Programs

- **Active Aeroelastic Wing**
  - **Joint AF/NASA Program**
  - **Eliminate Structural Weight**
  - **Using Modified F-18A**
  - **Flight Test Concept FY00**



- **Twist Adaptive Wing**
  - **Integral Torque Tube**
  - **No Seams, Low RCS**
  - **Flight Tests On UAV FY98**

More Electric Aircraft Technology



Goal: Replace ALL Aircraft Secondary Power With One Type: ELECTRIC

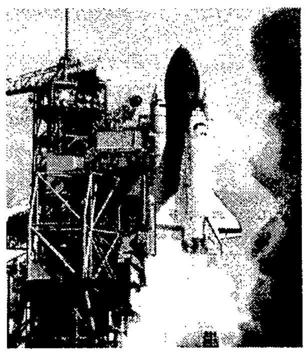
MEA Benefits

JTCG/AS

Maintainability
- Reduced Logistics Tail
- Eliminates CHS Support Equipment
- Improved MTBF
- Improved MTTR (LRU)

Design Payoffs
- Systems Level Weight Savings
- Improved System Survivability
- Reduced Vulnerability
- Increased Subsystem Design Freedom

O&S
- Increased Aircraft Sortie Rate
- Improved Life Cycle Costs
- Improved Mobility/Deployment



Performance
- Less Secondary Power Extraction
- Improved Thermal Management (Power on Demand)

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MEA Reduces Cost Of Global Power Projection

○ HYDRAULIC FLUIDS, LUBRICANTS, ASSOCIATED CLEANING SOLUTIONS

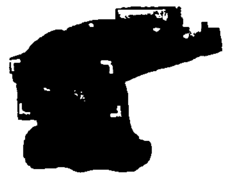
○ FLIGHT LINE BATTERY SUPPORT SHOP

○ 60 OF 458 MAINTENANCE MANPOWER (F-16)

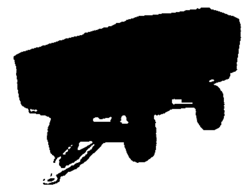
○ 3.5 OF 16 C-141 SORTIES (F-16)

SAVINGS IN $B's WITH IMPROVED WARFIGHTING

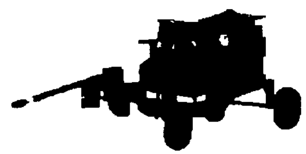
. . . BY ELIMINATING:



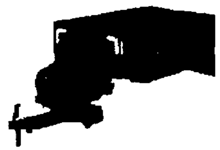
Electric Generator



Hydrazine Servicing Cart

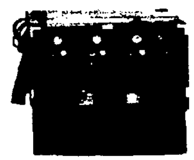


Hydraulic Servicing Cart



High Pressure Air Cart

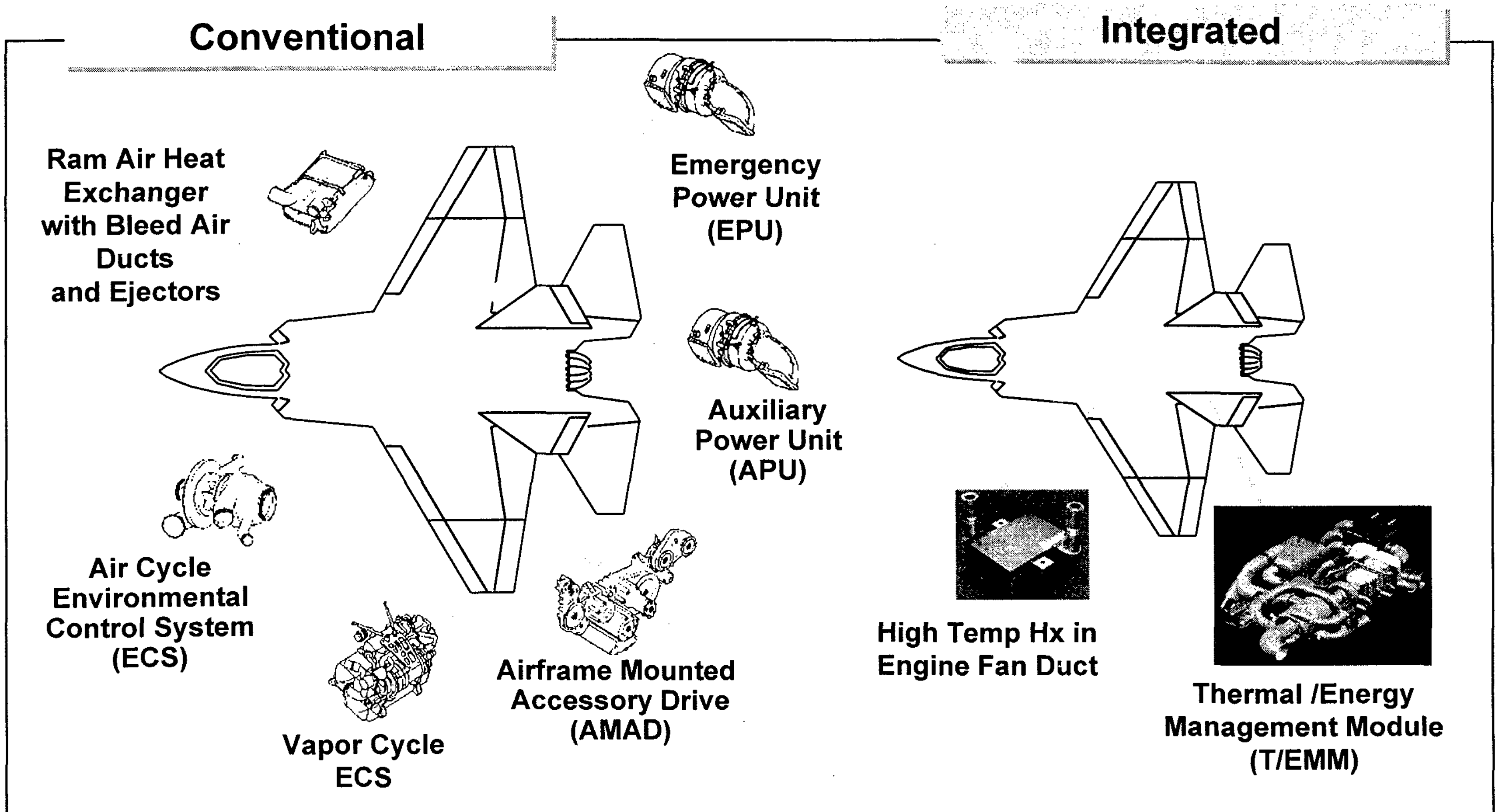
Air Conditioner



Hydraulic Mule

SC95/035

Thermal/Secondary Power



Improved Efficiency and Lower Equipment Count Enables Smaller, Lighter and Lower Cost Aircraft

Integrate Thermal/Secondary Power Benefits

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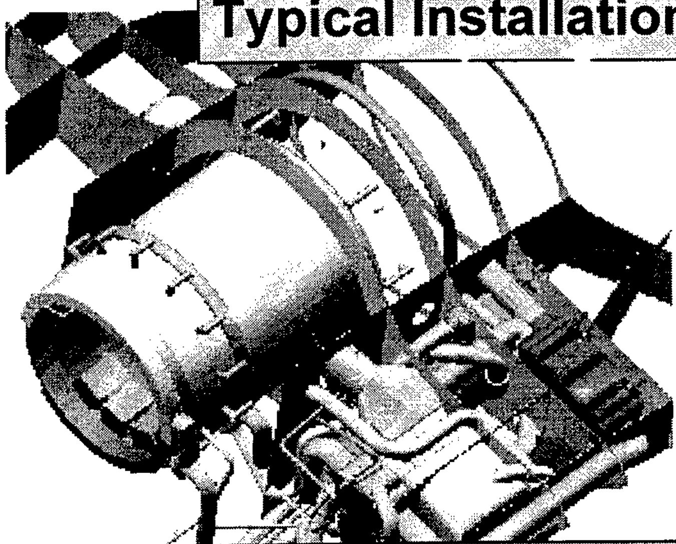
Typical Installation

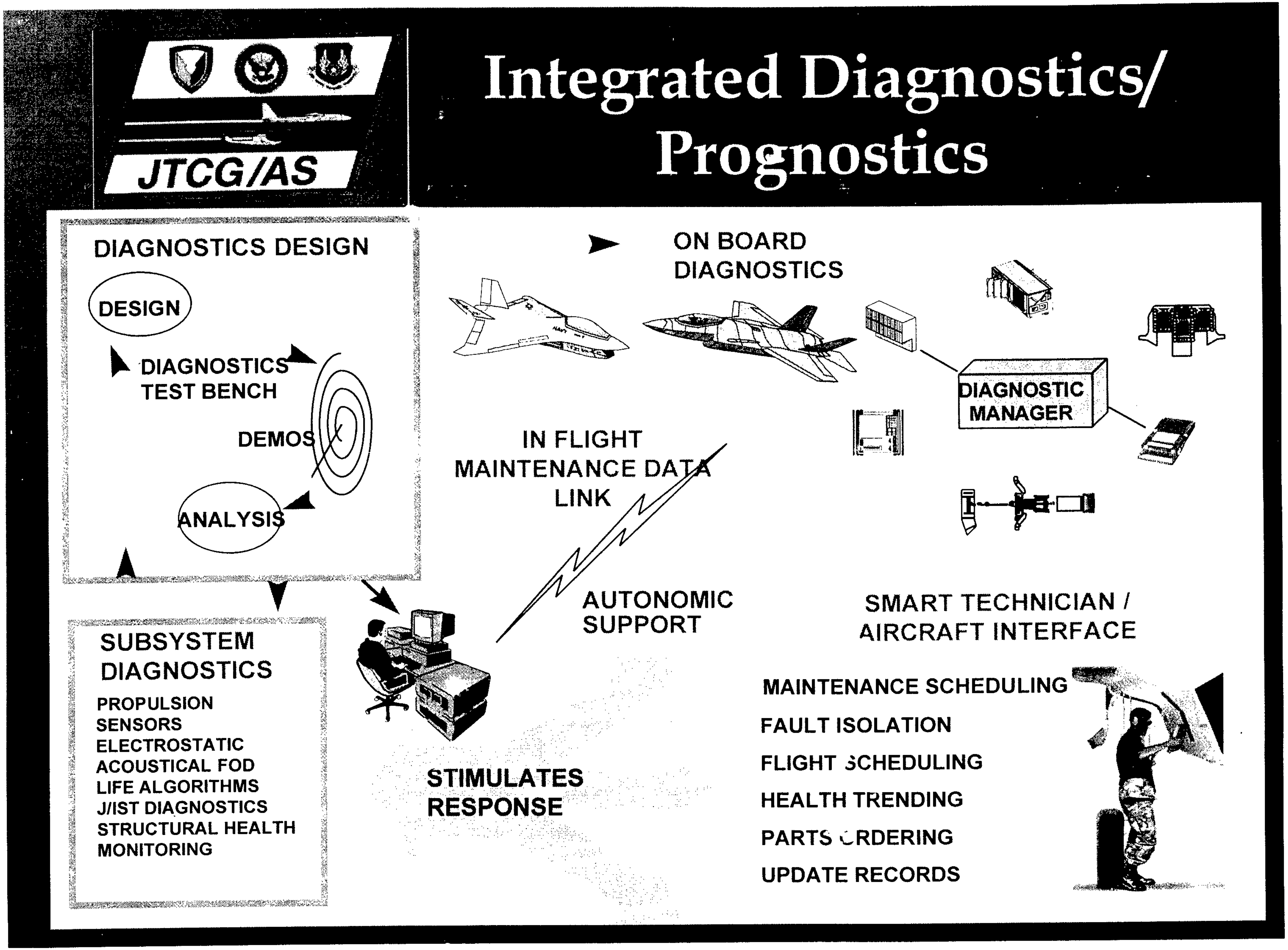


T/EMM System Saves 31 Cubic Feet

Provides Electrical Power and Cooling for Required Aircraft Subsystems Functions :

- Deck Edge Maintenance
- Stand Alone Start
- Ground Maintenance
- Main Engine Start
- Normal Flight
- Normal Flight with Electric Power
- Emergency Power - Stored Air
- Emergency Power - Ambient Air

- 3%- 5% Reduction in Procurement Cost
- 3%- 4% Reduction in LCC
- Up To 5.5% Reduction in TOGW or
- Up To 20% Improvement in Range ... Not Resized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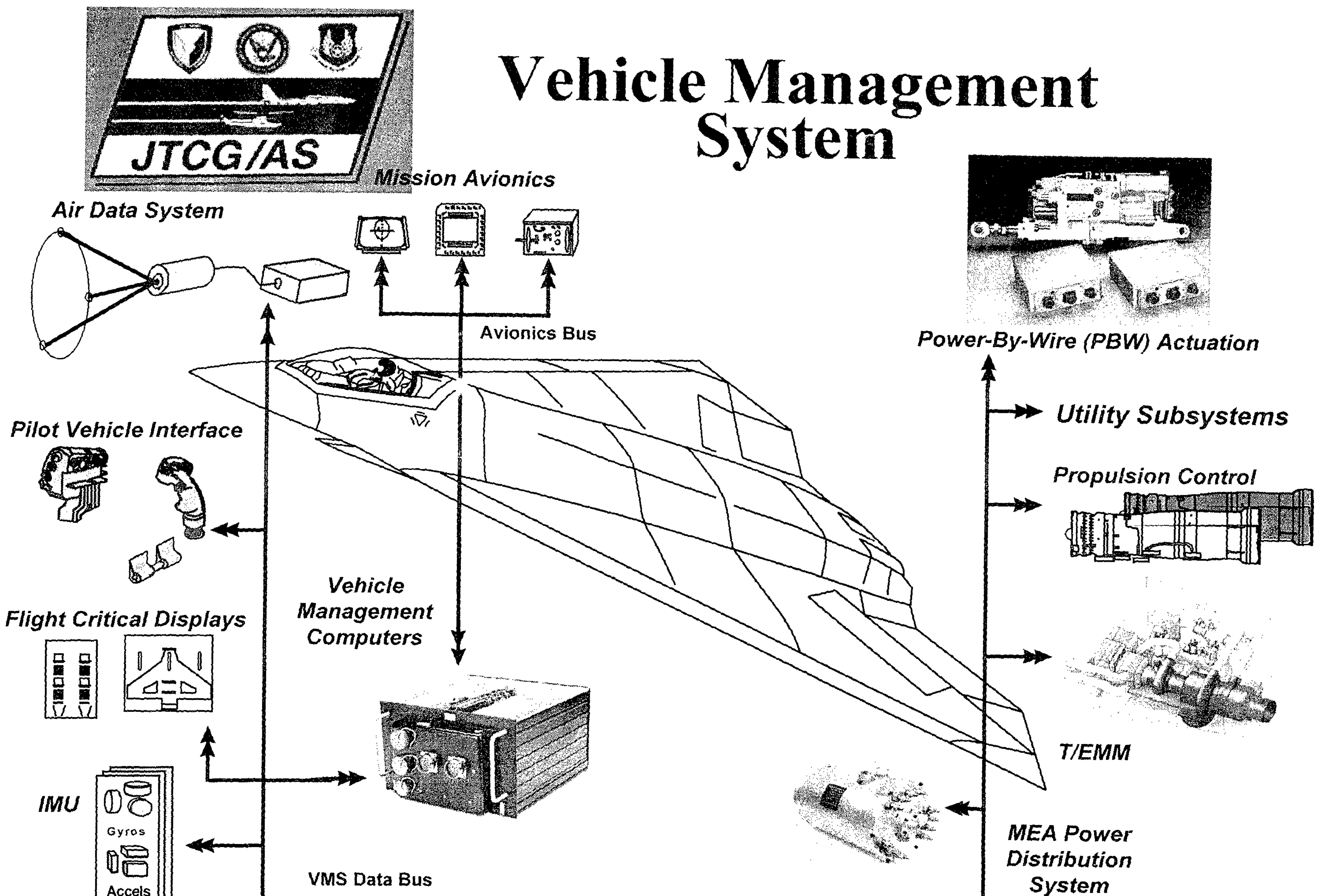
Integrated Diagnostics/
Prognostics
DIAGNOSTICS DESIGN
DESIGN
DIAGNOSTICS
TEST BENCH
DEMOS
ANALYSIS
ON BOARD
DIAGNOSTICS
DIAGNOSTIC
MANAGER
IN FLIGHT
MAINTENANCE DATA
LINK
AUTONOMIC
SUPPORT
SUBSYSTEM
DIAGNOSTICS
PROPULSION
SENSORS
ELECTROSTATIC
ACOUSTICAL FOD
LIFE ALGORITHMS
J/IST DIAGNOSTICS
STRUCTURAL HEALTH
MONITORING
STIMULATES
RESPONSE
SMART TECHNICIAN /
AIRCRAFT INTERFACE
MAINTENANCE SCHEDULING
FAULT ISOLATION
FLIGHT SCHEDULING
HEALTH TRENDING
PARTS ORDERING
UPDATE RECORDS

JTCG/AS

Integrated Diagnostics/ Prognostics

Diagnostic	Existing	Near Future
• Fault Prediction (Prognostics)	• Fixed estimate of life based on statistical projections	• Real-time estimate of remaining life assessment by tail #
• Fault Detection	• On-board BIT plus performance evaluation	• Real-time correlated BIT and data capture
• Fault Isolation	• Generally post flight with some fault tolerant redundancy • Predesigned FI manuals	• Interactive Portable Maintenance Aids (PMAs) & data transmsn for 2nd level FI
• Fault Analysis	• Paper instructions & gnd support equip • Remote engr function	• Remote data analysis using flight data downlink
• Fault Correction	• ECP process	• Real-time process improvement using on-line databases, rapid prototyping and flexible [illegible] techniques

Vehicle Management System



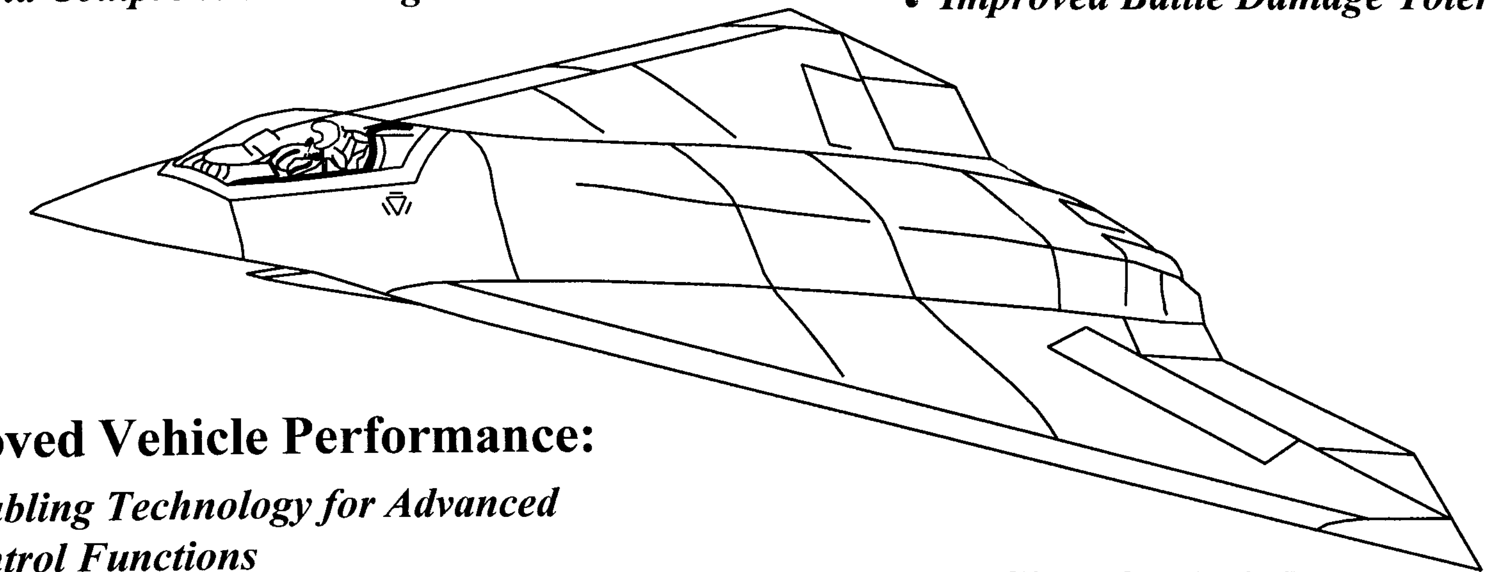
21-Oct-97

VMS Benefits

JTCG/AS

- **Improved Life Cycle Cost:**
  - *Use of Commercial Technologies and Practices*
  - *Reduced Hardware Count*
  - *Improved Design Tools and Techniques*
  - *Rapid Comprehensive Integrated V&V*

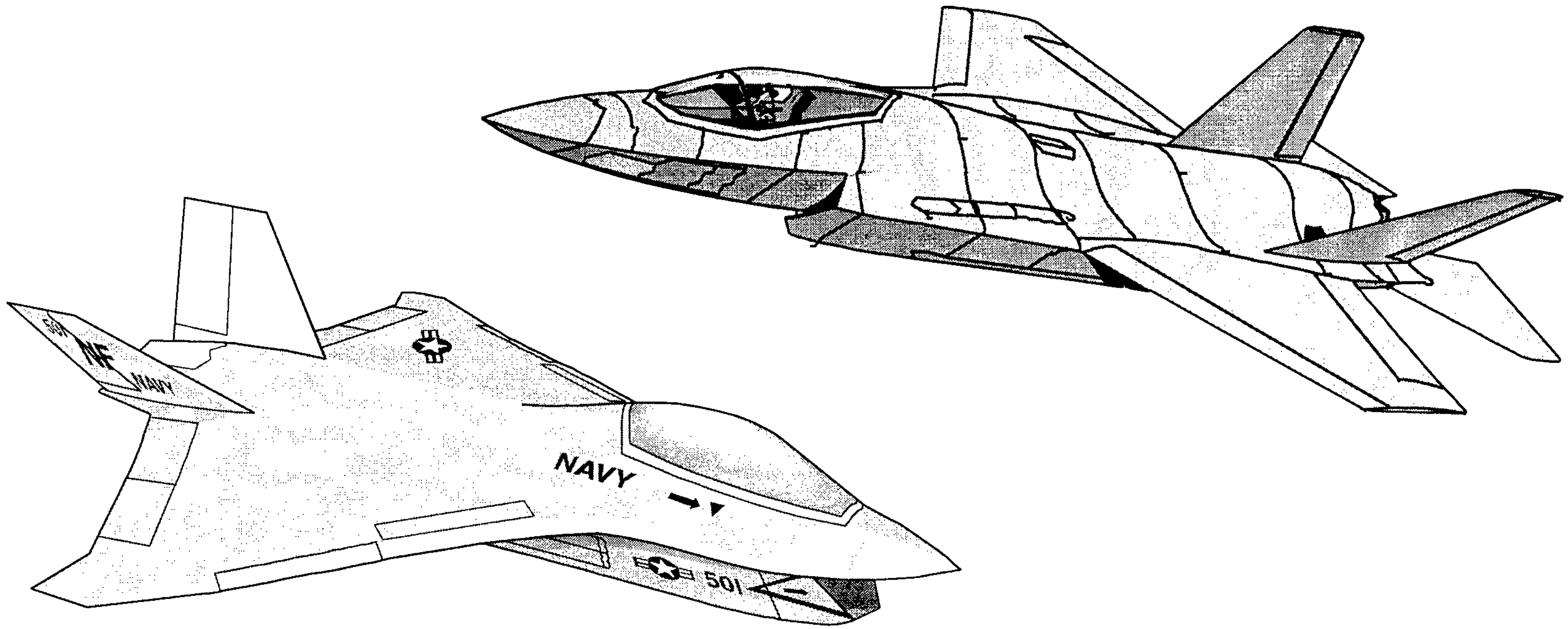
- **Improved Vehicle Survivability:**
  - *Improved EMI Tolerance*
  - *Increased Fault Tolerance*
  - *Improved Reliability*
  - *Improved Battle Damage Tolerance*



- **Improved Vehicle Performance:**
  - *Enabling Technology for Advanced Control Functions*
  - *Scaleable Open Architecture for Growth Potential*
  - *Modular Upgrades to Avoid Obsolescence*

- **Reduced Size & Weight:**
  - *Reduced Cabling Weight*
  - *Reduced Parts Count*

Pipe Dreams? Heads Up, Here Comes JSF!



Pound For Pound The Most "Integrated" Weapon System Built To Date!

Integration Survivability Impacts

PROS

- Smaller Cross Sections
- Less Waste Heat
- Reduced Computer Counts
- Reduced Wiring
- Better Damage identification
- Better Prognostics & Health Management
- Less Flammable Fluids

CONS

- Individual components can be critical for multiple systems
- Unknown failure modes
- Systems Becoming Critical That Weren't In The Past
- Mix of Critical & Non-Critical Software Muddies Reaction To Failures
- Allows Reduced Strength In Other Systems (such as structures)

JTCG/AS

That's Great, But What Do We Do?

First

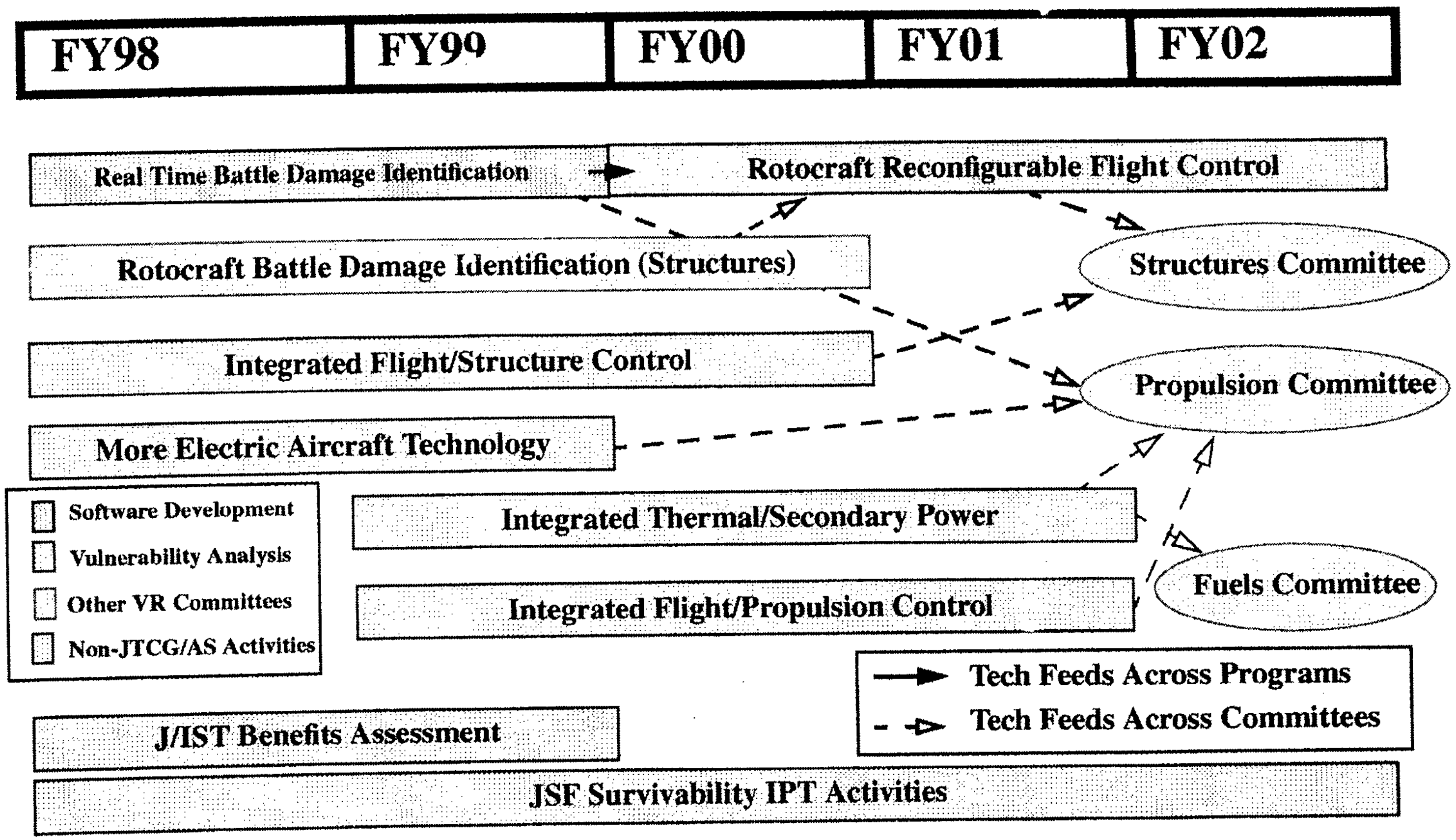
[redacted]

Then

[redacted]

Roadmap To Answers

JTCG/AS Flight Systems Committee Programs



JTCG/AS

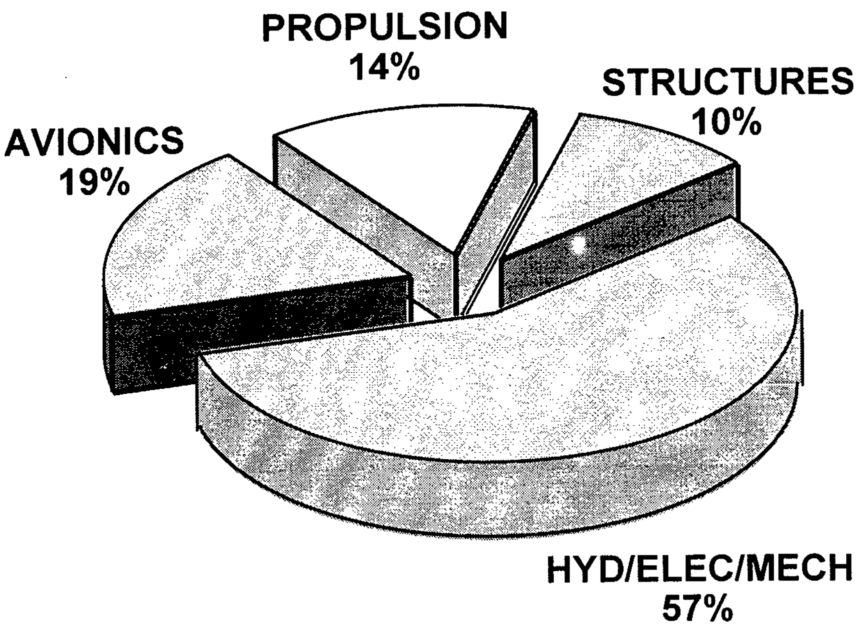
Conclusions

- Performance Increase, Cost Reduction, Driving Integration Of Aircraft Systems
- Decreased Survivability Due To Increased Vulnerability, i.e., Single-Point Failures?
- Increased Survivability Due To Decreased Susceptability, i.e., Increased Performance And Reduced Observability?
- Studies Underway, Or Planned, Assessing Vulnerability Impacts Of Integration And Possible Risk Reduction

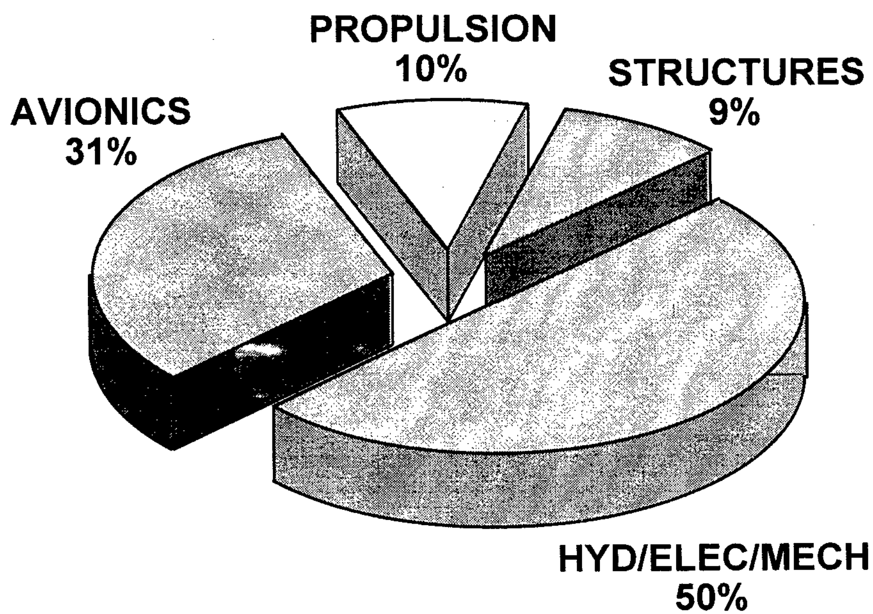
Community Is Stepping Up To The Challenges Posed By Systems Integration

AIR FORCE / NAVY FIGHTER AIRCRAFT

THE PROBLEM



DOWNTIMES



FAILURES

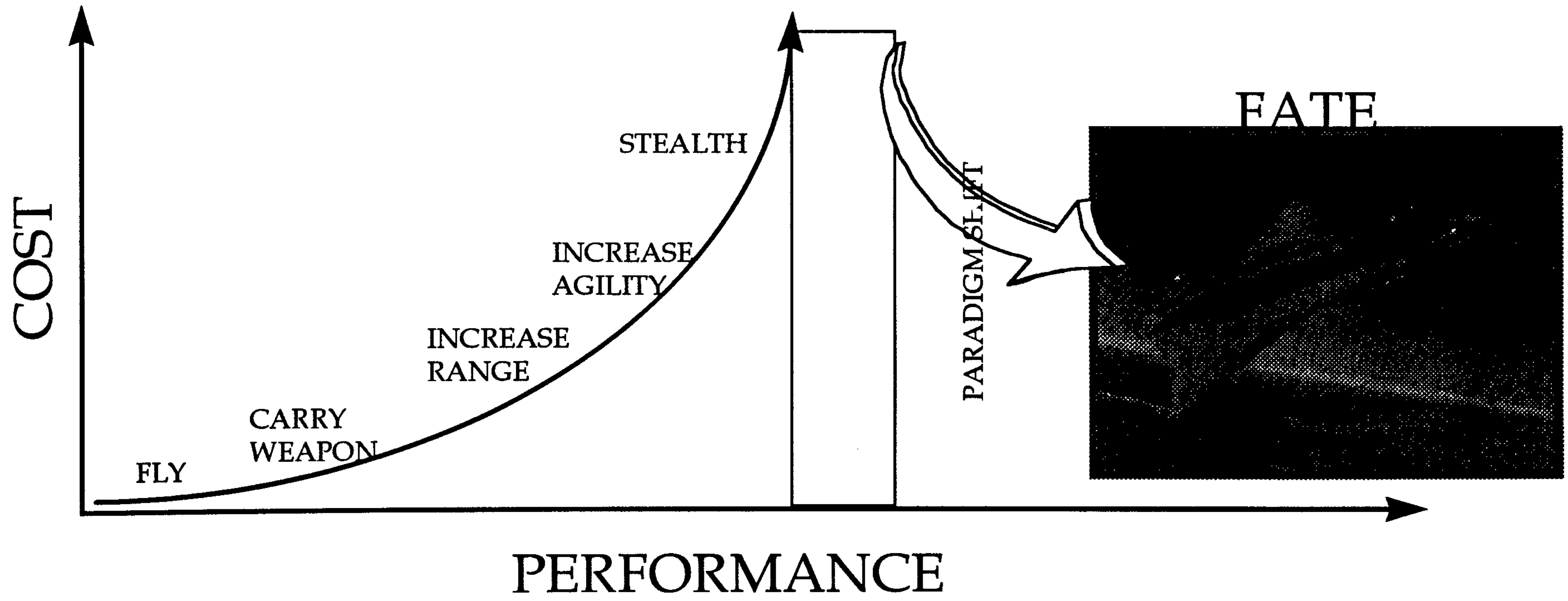
AIR VEHICLES TECHNOLOGY:

BETTER PERFORMANCE, REDUCED VULNERABILITY

Col Gerry Hasen
Acting FI Director

VISION

BREAK THE PARADIGM THAT HIGH PERFORMANCE CAN ONLY BE ACHIEVED AT HIGH COST



ENABLE DRAMATIC COST REDUCTIONS AND PERFORMANCE GAINS THROUGH THE DEVELOPMENT OF MULTIDISCIPLINARY AIRFRAME SYSTEMS

THE FIXED WING VEHICLE TECHNOLOGY DEVELOPMENT APPROACH PROCESS

TDA

- TO DEVELOP A 15 YEAR PLAN LEADING TO A PROGRAM FOR DOD/NASA/ INDUSTRY/ACADEMIA MILITARY FIXED WING VEHICLE S&T INVESTMENT IN FIVE TECHNOLOGY EFFORTS:
  - AERODYNAMICS
  - FLIGHT CONTROL
  - STRUCTURES
  - SUBSYSTEMS
  - INTEGRATICN/DEMONSTRATION

9/10/97

SCOPE

TDA

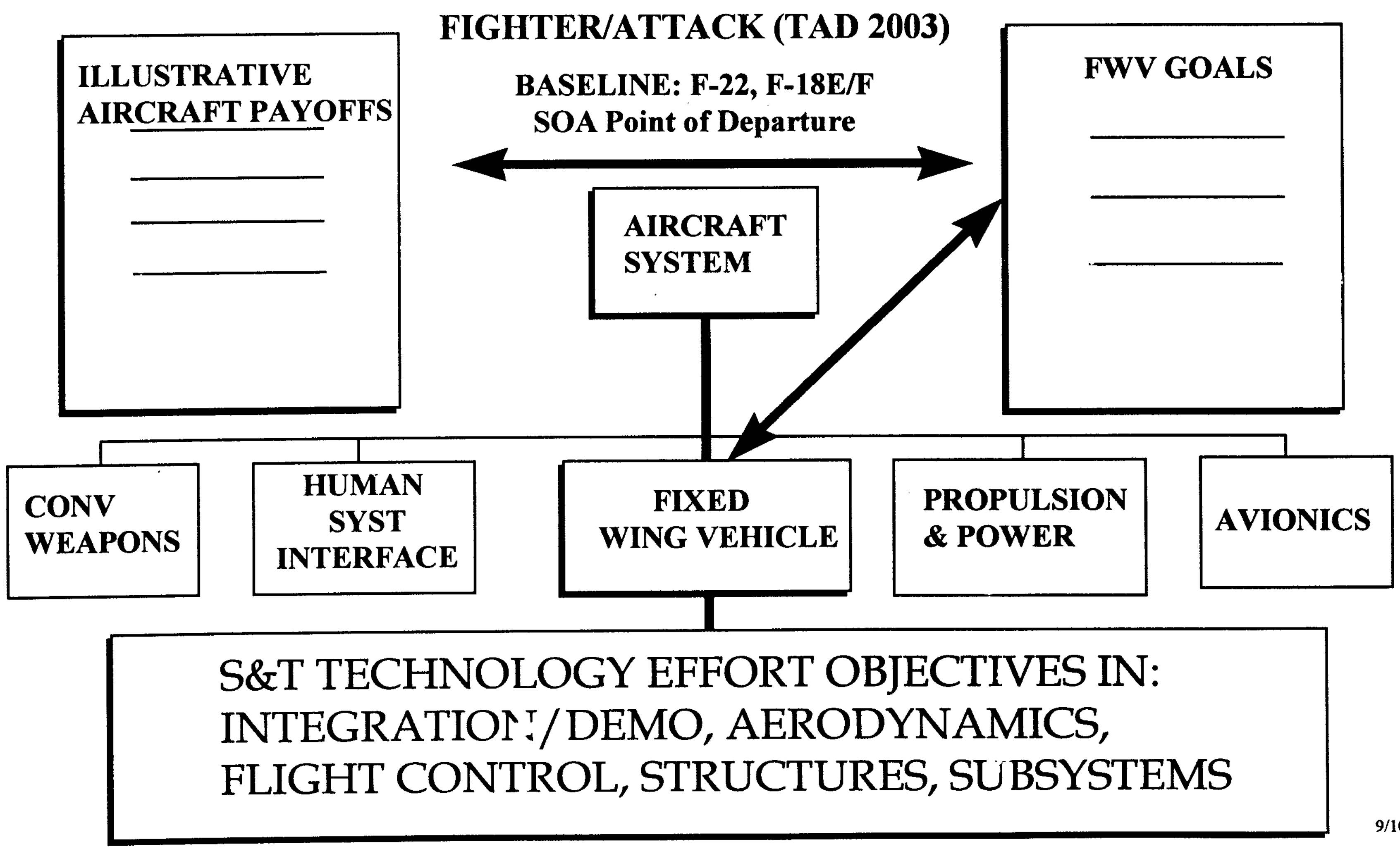
- THREE FAMILIES OF AIRCRAFT/ POINT OF DEPARTURE, STATE-OF-THE-ART

FIGHTER/ATTACK	F-22, F-18E/F
AIRLIFT/PATROL/ BOMBER	C-17, P-3, B-2
SOF	H/MC-130J

- THREE TIMEFRAMES: 2003, 2008, 2013

OVERVIEW DIAGRAMS
(one for each Family and Timeframe)

TDA



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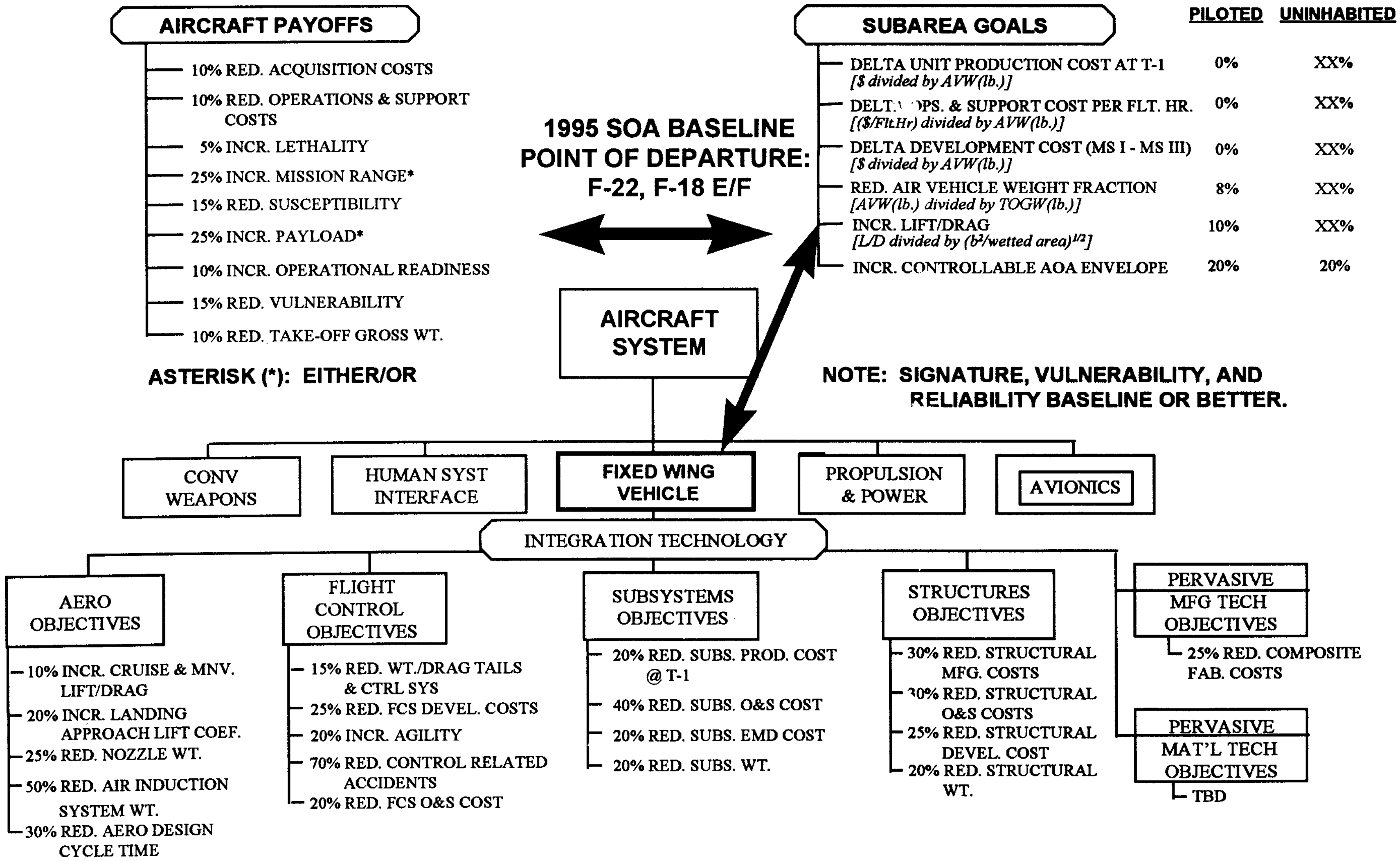
FWV-TDA S&T PAYOFFS, GOALS, AND OBJECTIVES
FIGHTER/ATTACK (PHASE I)



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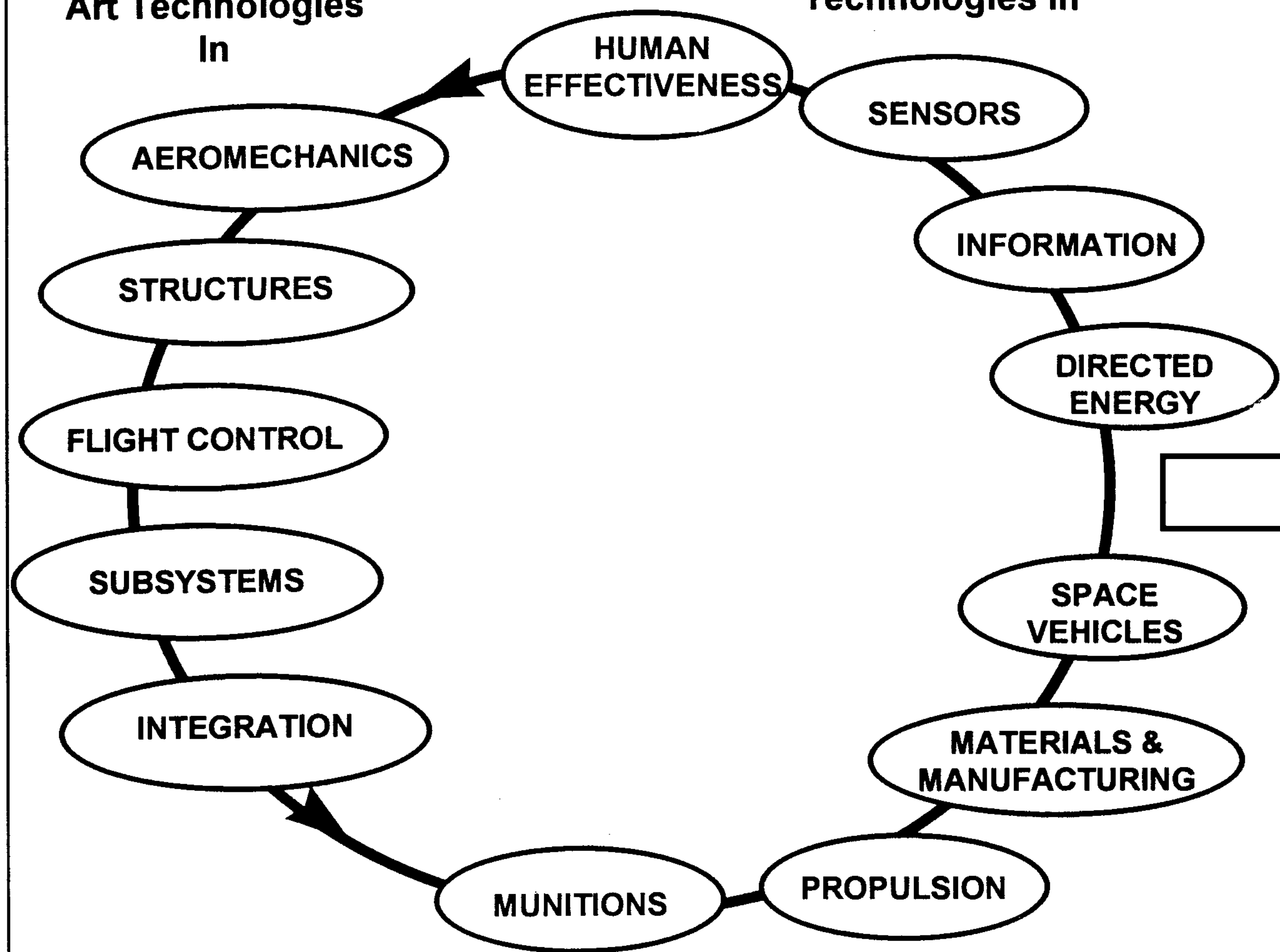
Air Vehicles Technology Development

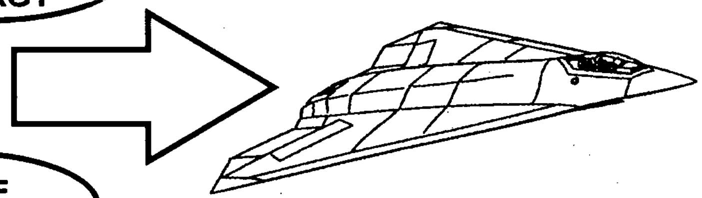
New or State of the Art Technologies In

Integrate With Technologies In

Yielding



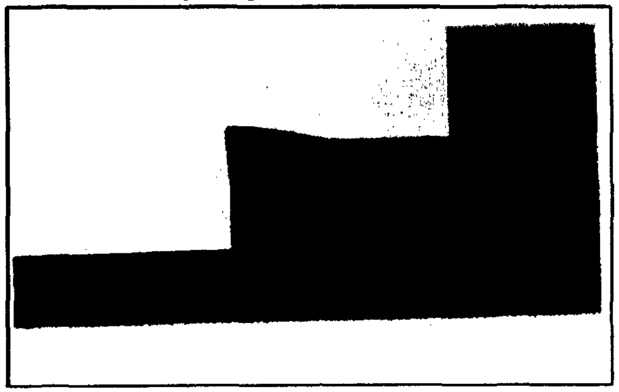
Evolutionary / Revolutionary Technology Sets & Design Methods



To Enable New & Improved Aerospace Vehicles

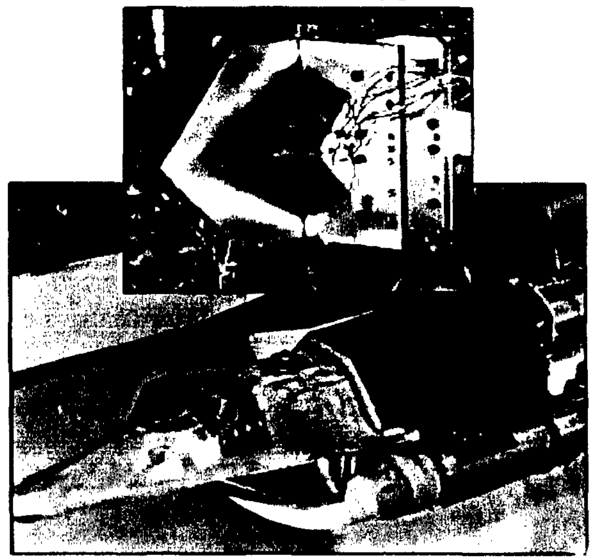
AEROMECHANICS CORE COMPETENCIES

AERO CONFIGURATION



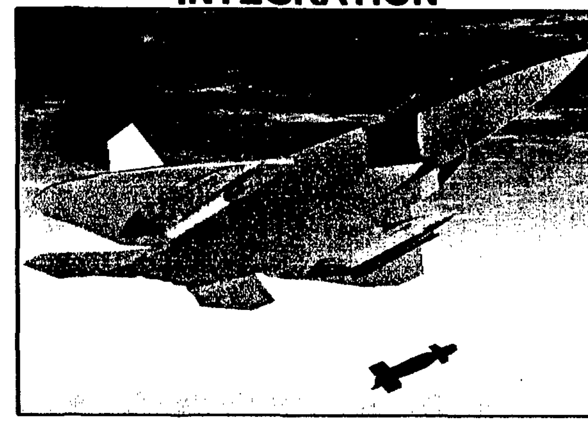
- Aero Configs for Survivable A/C
- High L/D Technologies

AIRFRAME PROPULSION INTEGRATION



- Affordable, Survivable Inlets
- Affordable, Survivable Nozzles

AIRFRAME WEAPONS INTEGRATION



- Weapons Carriage for Survivable A/C
- Active Flow Control of Bays

COMPUTATIONAL FLUID DYNAMICS

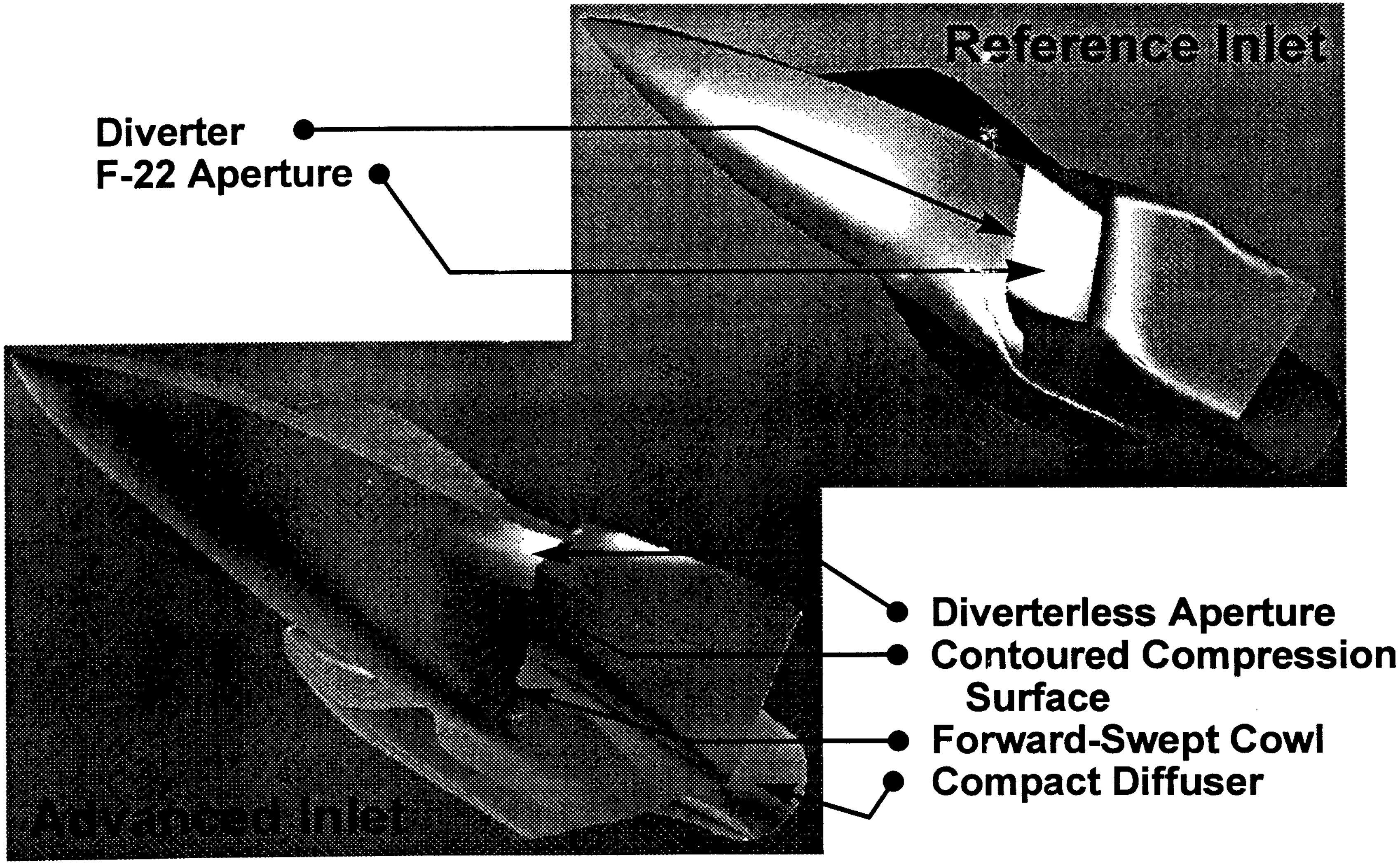
- Basic Research for CFD and CEM
- Aero Design Optimization CFD

EXPERIMENTAL AERO

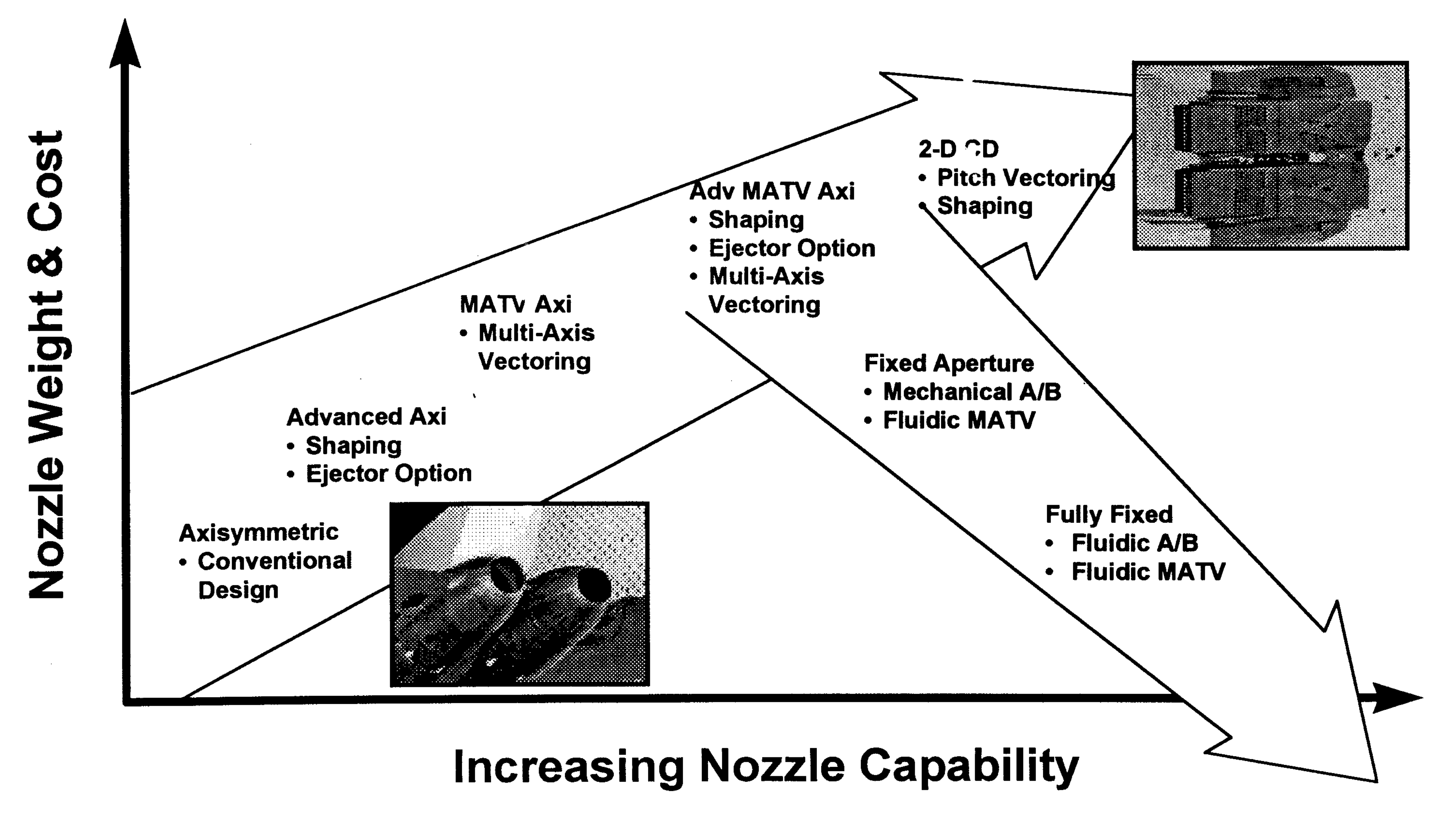
- Subsonic Aerospace Res Lab
- Vertical Wind Tunnel

ADVANCED INLET INTEGRATION

System Features of Reference and Advanced Inlets

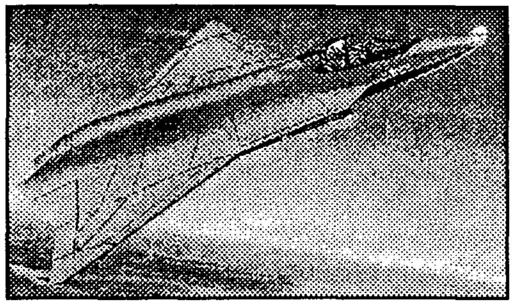


Why the Fixed Nozzle Approach?



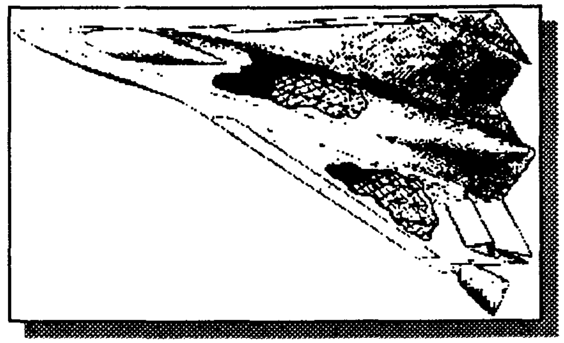
STRUCTURES TECHNOLOGY PROGRAMS

Structural Technology Integration



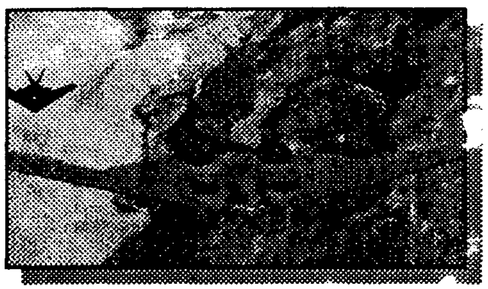
- *Affordable Airframe Structures*
- **Active Aeroelastic Structures**
- **Multifunctional Airframe Structures**
- *Multidisciplinary Design and Analysis Methods*

Smart Structures



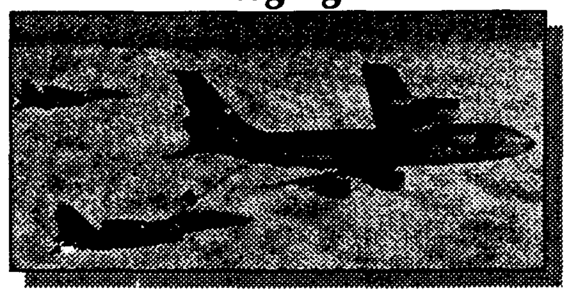
- **Adaptive Structures**
- *Vibration Suppression*
- *Smart Skins*

Extreme Environment Structures



- *Structural Temperature Control*
- *Affordable Exhaust-Washed Structures*

Structural Integrity of Aging Aircraft



- *Repairs*
- **Corrosion/Fatigue**
- *Widespread Fatigue Damage*
- **Dynamics & Noise Suppression**

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STRUCTURAL TECHNOLOGY INTEGRATION
Affordable Airframe Structures

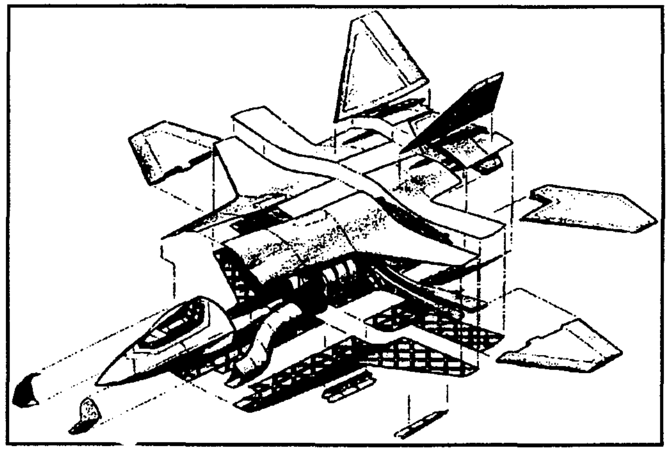
COMPOSITES
AFFORDABILITY INITIATIVE

OBJECTIVE

- Demonstrate & Validate Inherent Benefits of Composite Technology
  - Couple innovative designs to manufacturing processes

APPROACH

- Develop & Validate Enabling Technologies
- Establish Design Concepts & Methods
- Establish Industrial-Base Confidence



PAYOFF

- Viable Industrial Base for Affordable Composites

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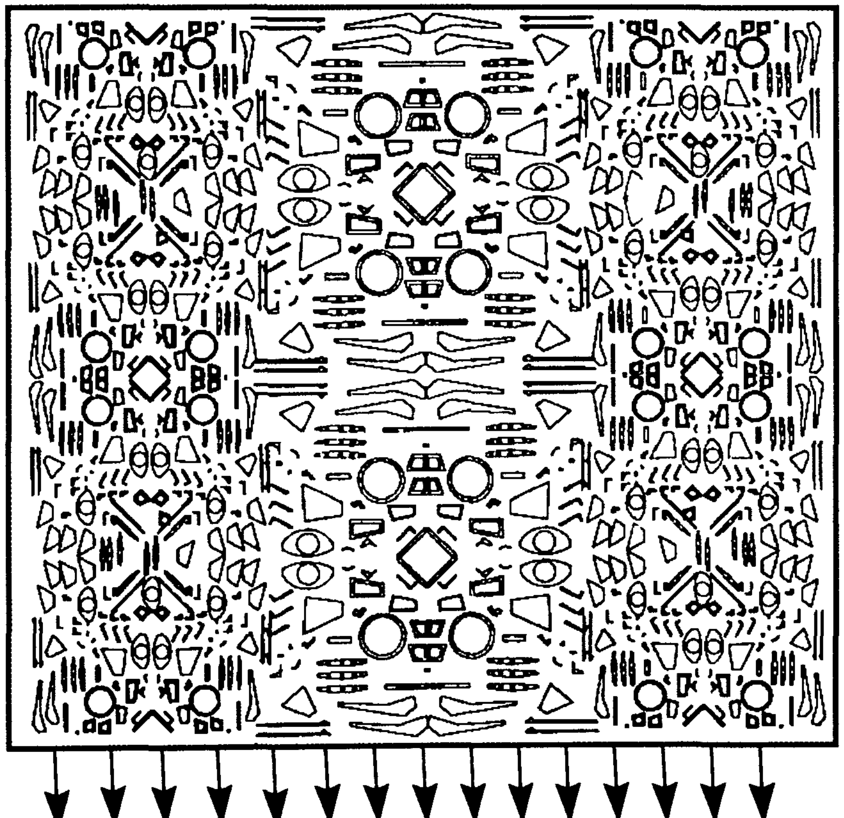
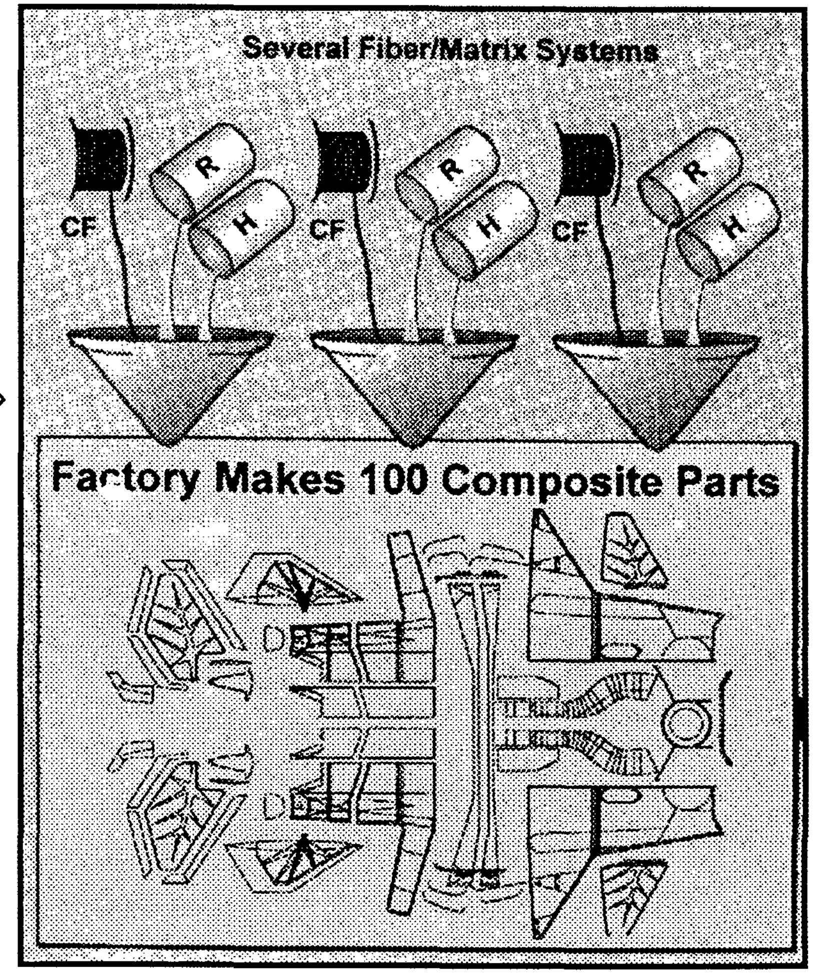
Traditional Airframe



Factory Activity is Primarily Assembly

~11,000 Metal Component-
~600 Composite Components
~135,000 Fasteners
High $ Vendor Markup

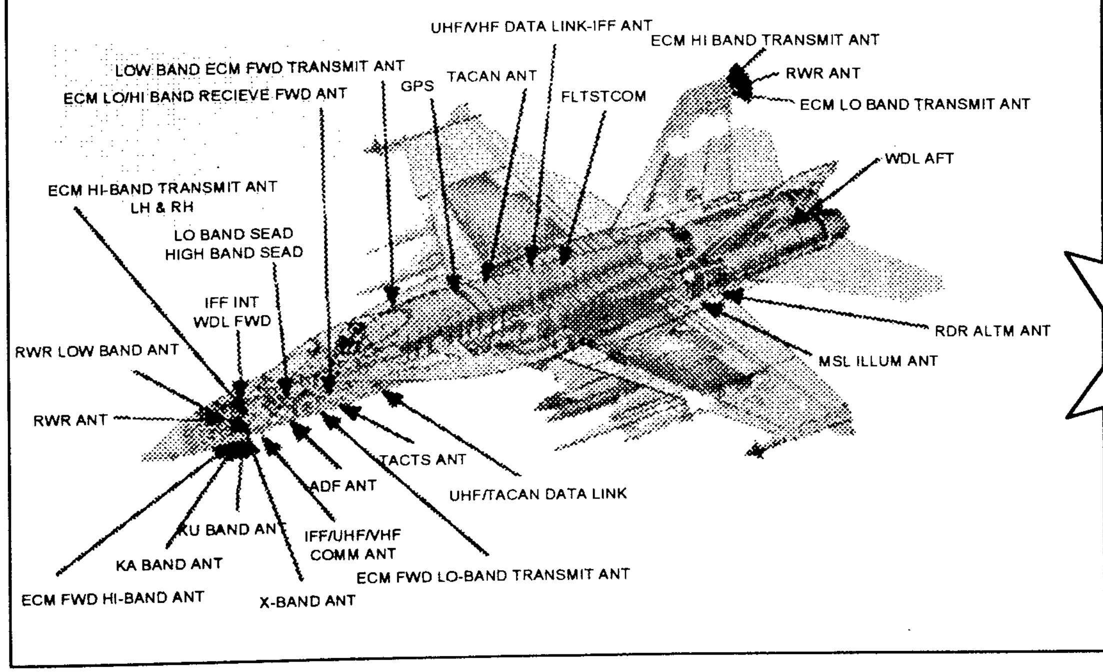
Goal for Unitized Airframe

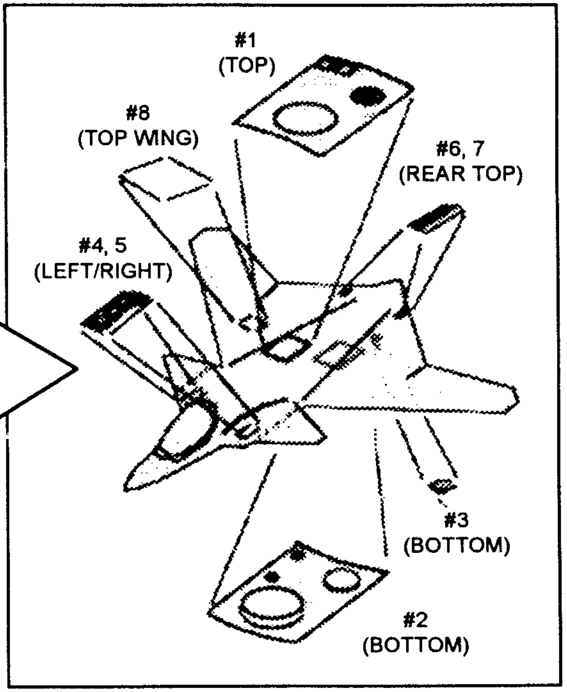


~450 Metal Components
~6000 Fasteners
89% Composite

SMART STRUCTURES
Smart Skins

CONFORMAL LOAD BEARING ANTENNA STRUCTURE





TODAYS PROBLEM

- NUMEROUS SINGLE FUNCTION APERTURES
- PARASITIC INTRUSIVE/EXTRUSIVE
- NOT LOADBEARING
- REDUNDANT & LIMITED RF PERFORMANCE
- ANTENNA PERFORMANCE COMPRISED
- STRUCTURAL PERFORMANCE COMPROMISED

CLAS SOLUTION

- FEW MULTIFUNCTION ANTENNAS
- LOADBEARING/CONFORMAL
- APERTURE SIZED FOR PERFORMANCE
- PERFORMANCE LOCATED APERTURE
- STRUCTURAL EFFICIENCY MAINTAINED

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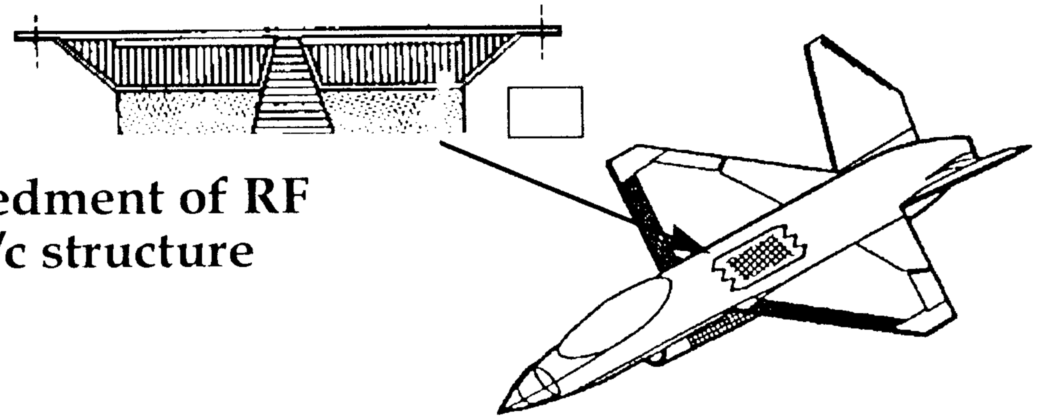
SMART STRUCTURES
Smart Skins

CONFORMAL LOAD BEARING
ANTENNA STRUCTURE



OBJECTIVE

Develop & demonstrate embedment of RF apertures in load-bearing a/c structure

APPROACH

- Design and fabricate upper and lower fuselage structure
  - Incorporate load-bearing wide-band antenna
- Perform ground test of full-scale component structure
  - Limit load tests
  - Electromagnetic performance

IMPACT

- Improved survivability
- Better antenna performance (range and coverage enhancements)
- Drag reduction / range improvement
- Cost savings (e.g., $250K per airframe on F-22)
- Weight savings (e.g., 70 lbs per airframe on F-22)

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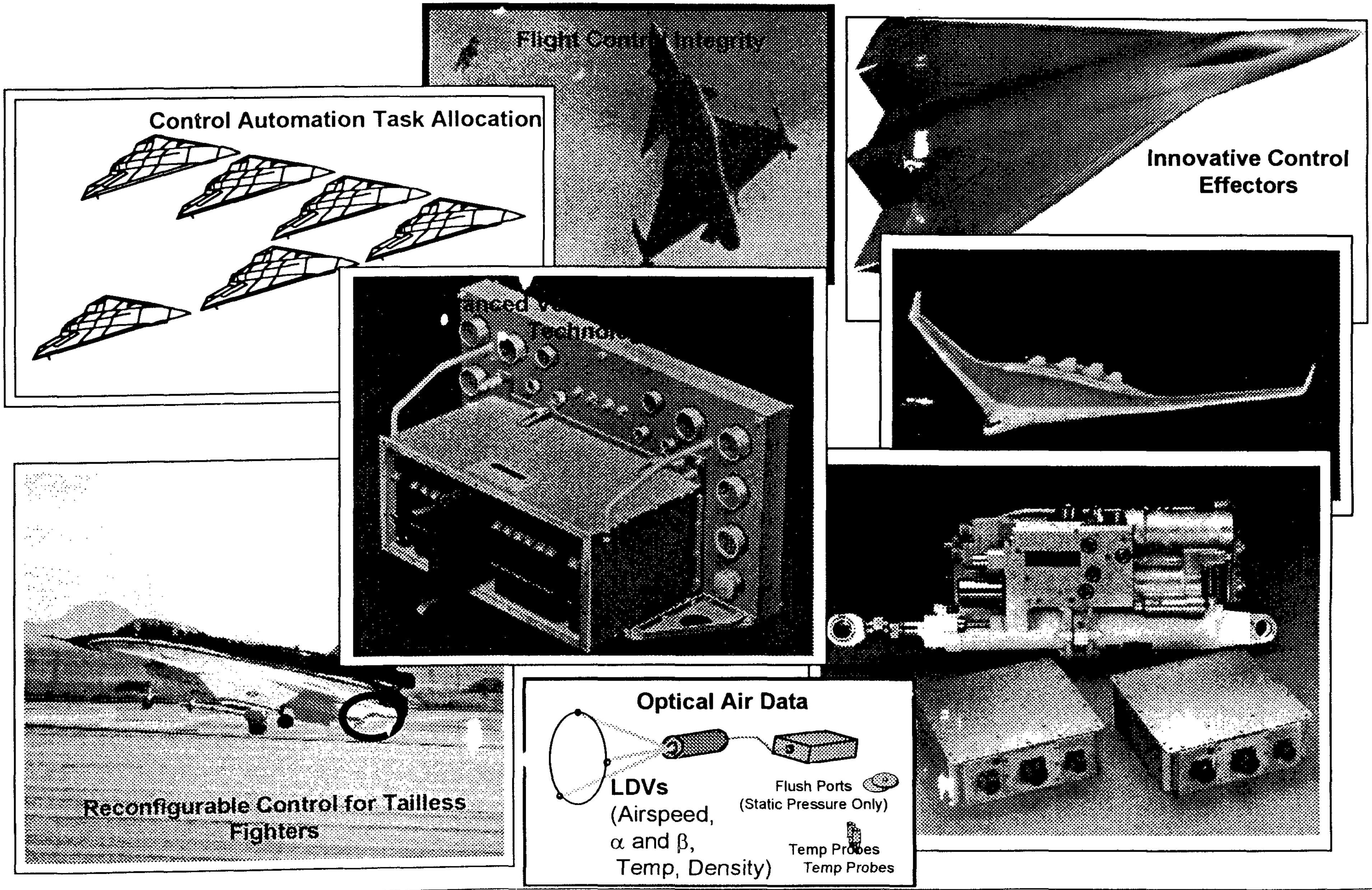
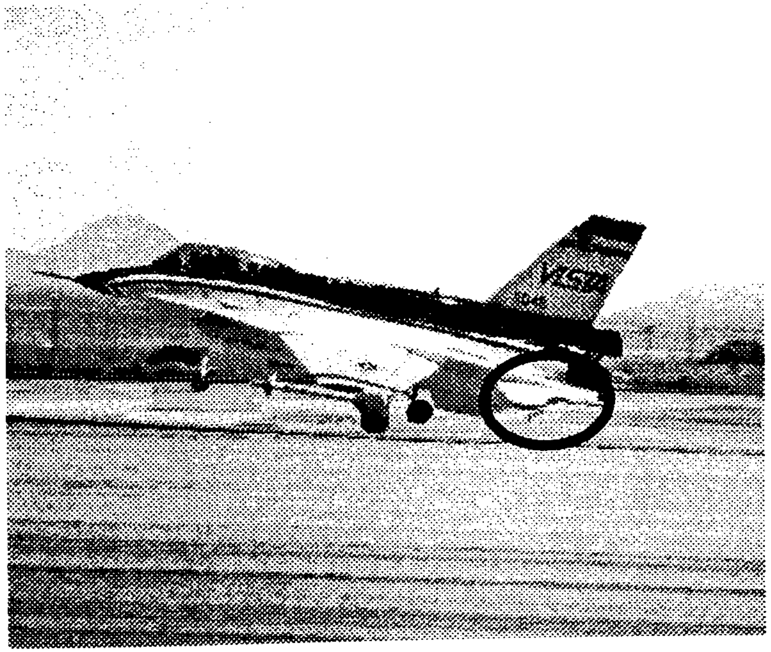
MAJOR FLIGHT CONTROL PROGRAMS



Self-Designing Controller

Wright Laboratory, Air Force Office of Scientific Research, Lockheed Martin, Barron and Associates, and Calspan



Objective

Develop and flight test adaptive control laws to optimize performance

Payoff

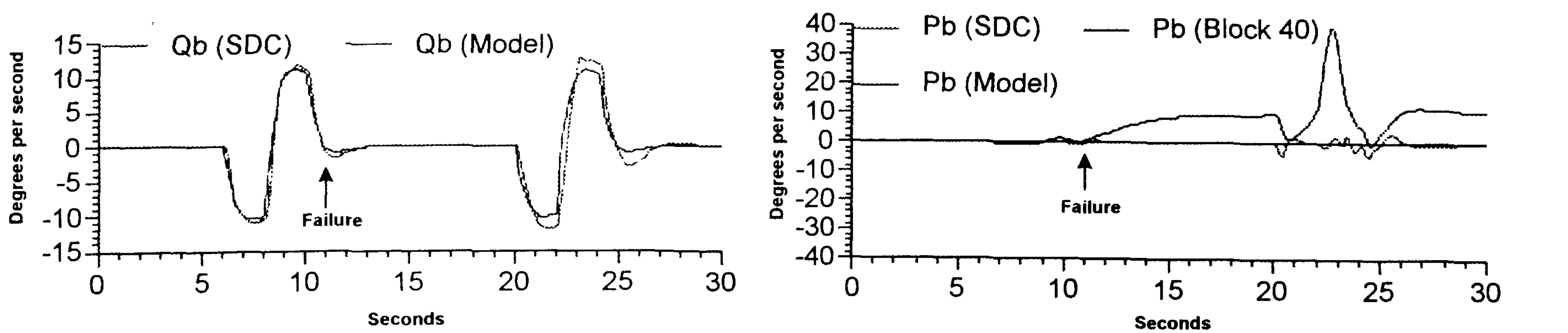
- **Damage tolerance**
- **Affordable design methodology**

Major Accomplishment: Land with Failures

574

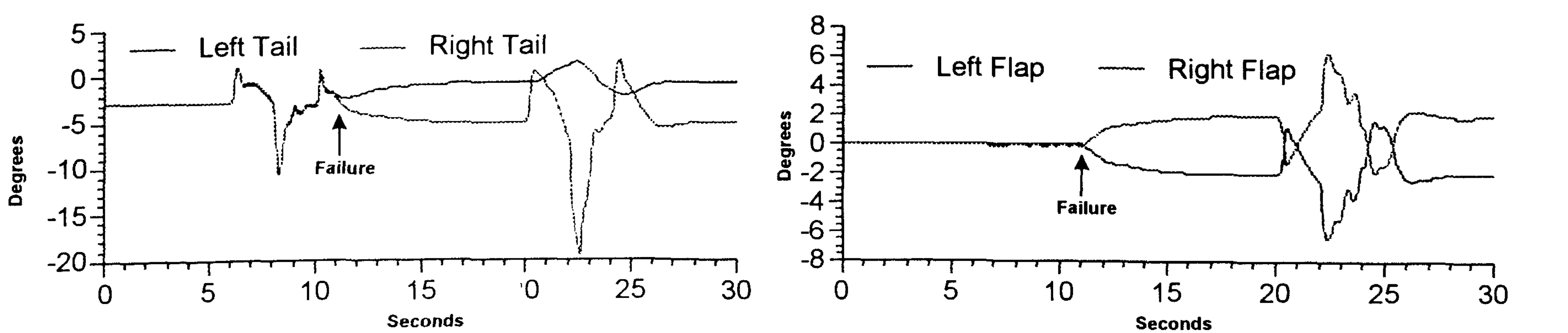
SELF-DESIGNING CONTROLLER
Simulation Results

Pitch and Roll Responses to Pitch Doublet Command
0% Effective Left Horizontal Tail at 11 Sec.



Aircraft Body Axis Pitch Rate

Aircraft Body Axis Roll Rate

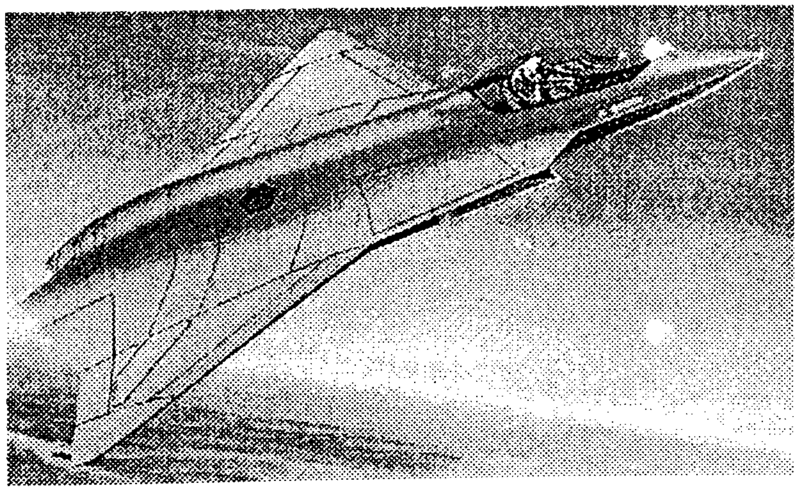


Left and Right Horizontal Tail Position

Left and Right Flap Position

Reconfigurable Control for Tailless A/C (RESTORE)

Wright Laboratory, Lockheed Martin Tactical Aircraft Systems, McDonnell Douglas Aircraft



Objective

On-line control design

- multi-axis instabilities
- coupled effectors

Payoff

- Reduced life cycle cost
- Increased aircraft survivability

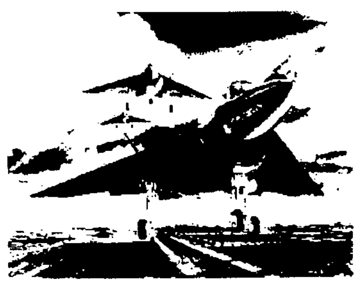
Power-By-Wire Actuation
System Benefits

- Enabling Technology for More Electric Aircraft (MEA)
- Pervasive to New A/C Designs & Retrofit/Upgrade

Maintainability
- Reduced Logistics Tail
- Eliminates CHS Support Equipment
- Improved MTBF
- Improved MTTR (LRU)

Design Payoffs
- Systems Level Weight Savings
- Improved System Survivability
- Reduced Vulnerability
- Increased Subsystem Design Freedom

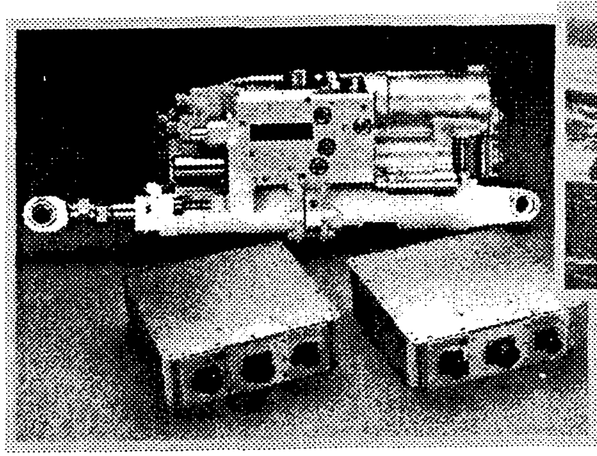
O&S
- Increased Aircraft Sortie Rate
- Improved Life Cycle Costs
- Improved Mobility/Deployment

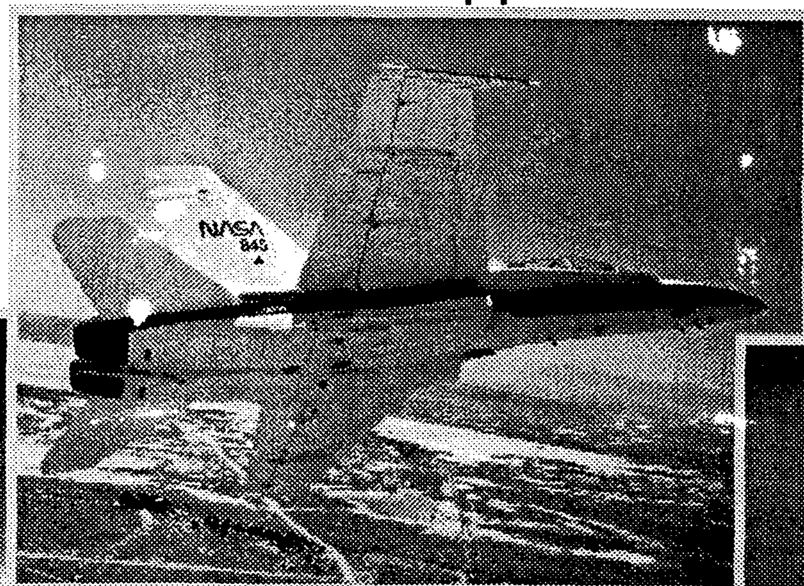


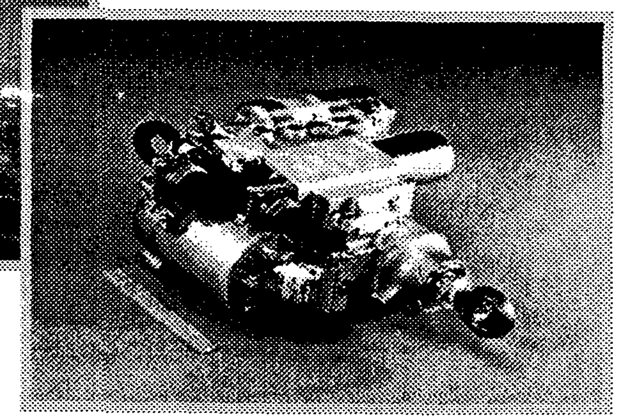
Performance
- Less Secondary Power Extraction
- Improved Thermal Management (Power on Demand)

Power-By-Wire Actuation Flight Validation

Phased Approach

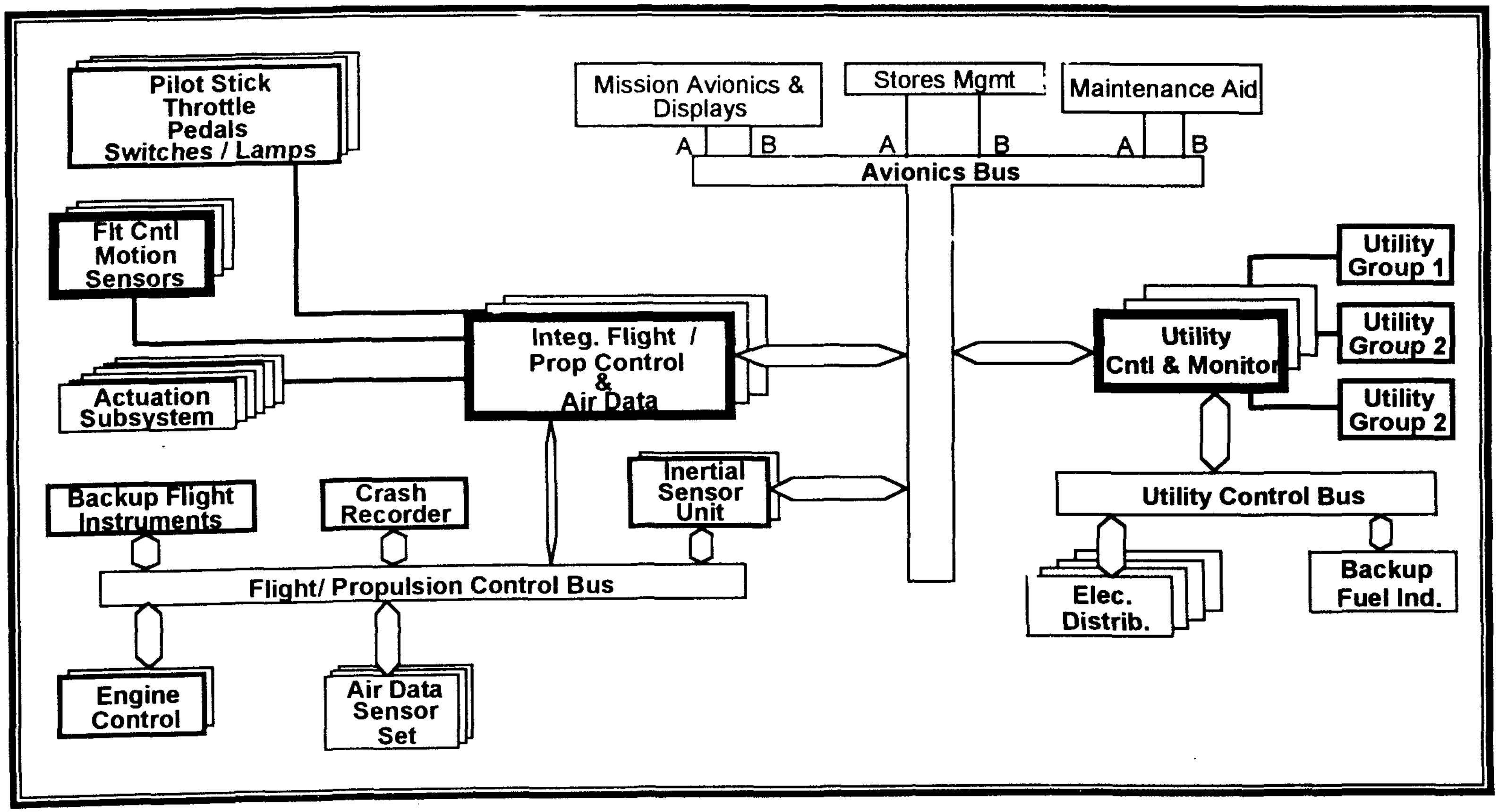






- Joint DoD, Industry IRAD, NASA (Air Force Lead)
- Electrohydrostatic Actuation
- Electromechanical Actuation
- PBW Aileron Flight Validation - 1996-1998
- PBW Stabilator Flight Validation - 2000-2002

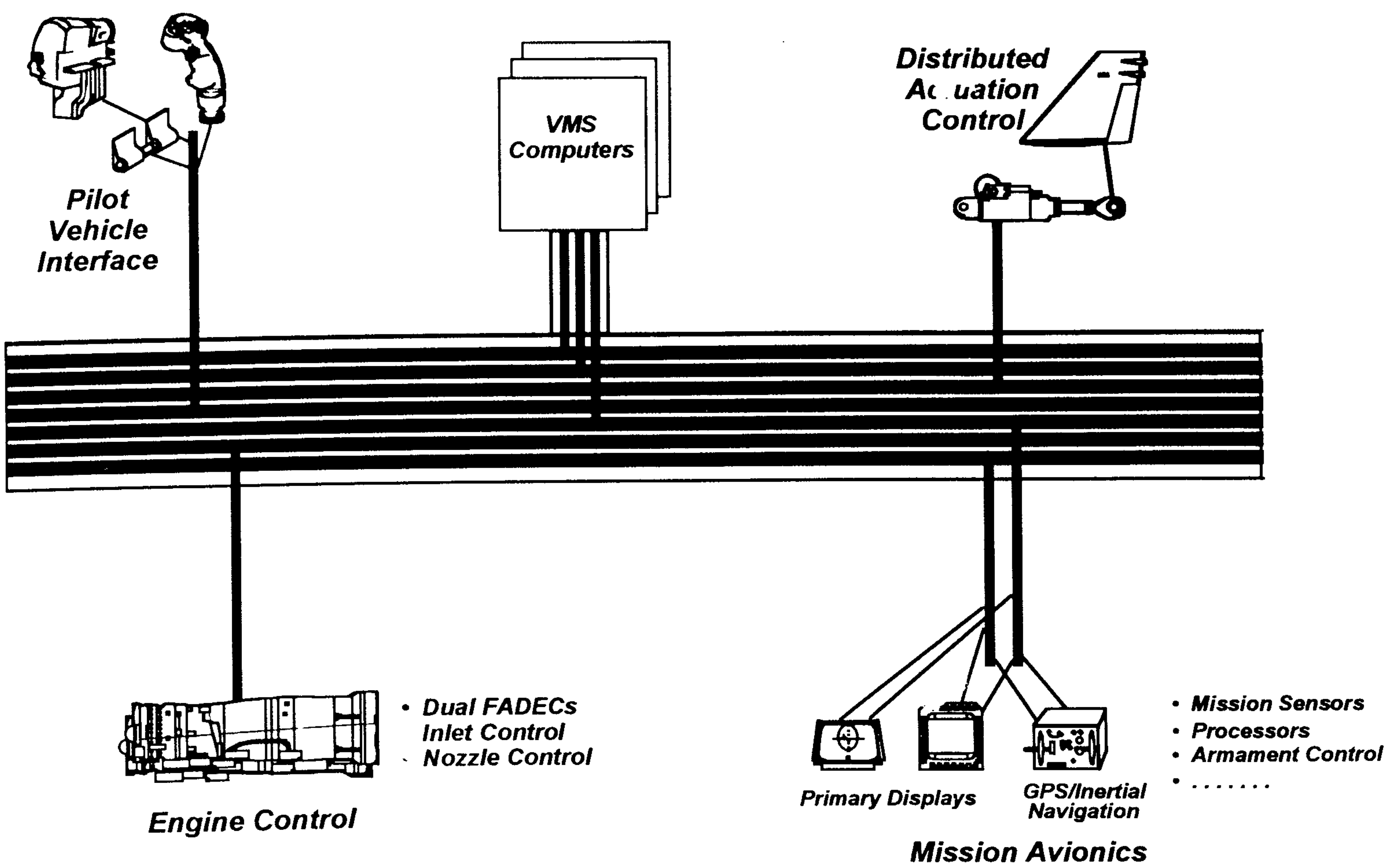
Reference Vehicle Management System



Photonic Vehicle Management System

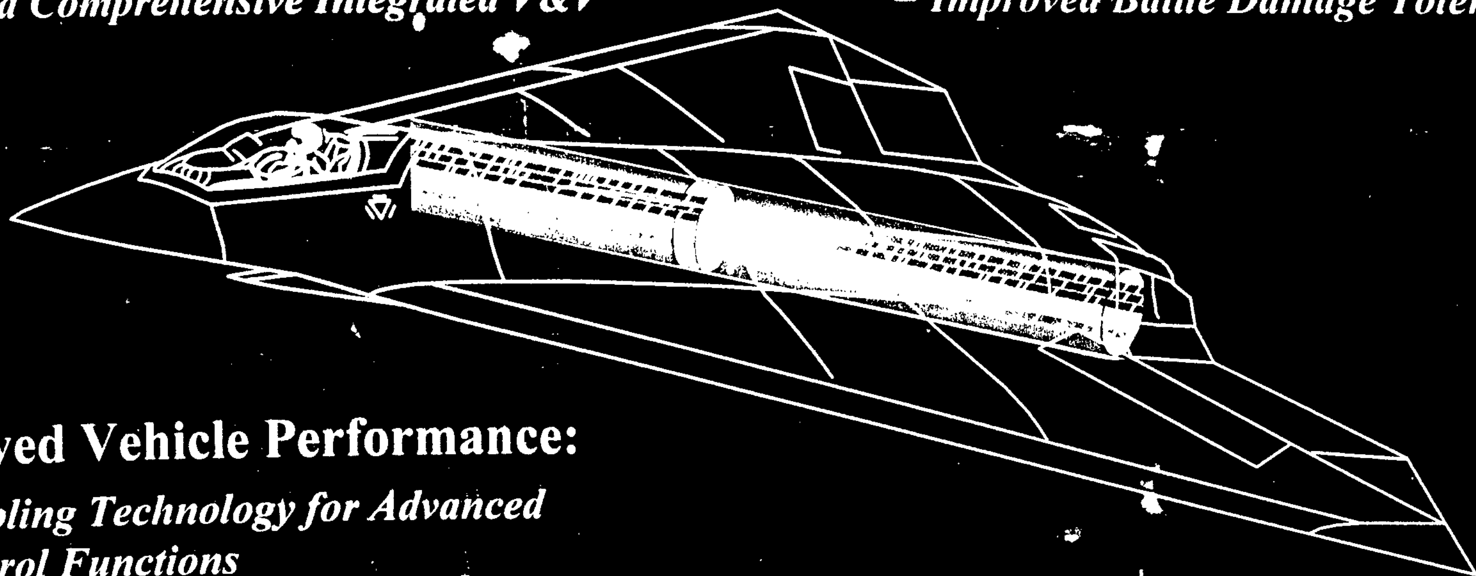
(TAD 2010)

Wavelength Division Multiplexing on Single Fiber



Photonic VMS Architecture Benefits

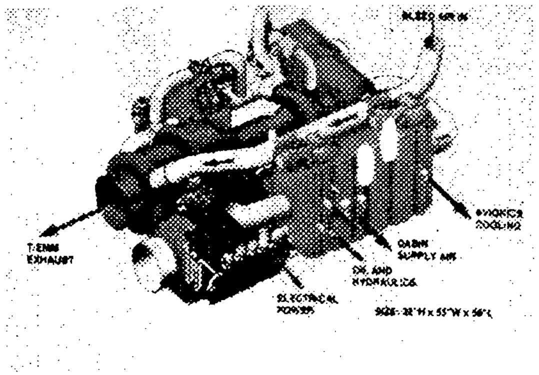
- **Improved Life Cycle Cost:**
  - *Use of Commercial Technologies and Practices*
  - *Reduced Hardware Count*
  - *Improved Design Tools and Techniques*
  - *Rapid Comprehensive Integrated V&V*
- **Improved Vehicle Survivability:**
  - *Improved EMI Tolerance*
  - *Increased Fault Tolerance*
  - *Improved Reliability*
  - *Improved Battle Damage Tolerance*



- **Improved Vehicle Performance:**
  - *Enabling Technology for Advanced Control Functions*
  - *Scaleable Open Architecture for Growth Potential*
  - *Modular Upgrades to Avoid Obsolescence*
- **Reduced Size & Weight:**
  - *Reduced Cabling Weight*
  - *Reduced Parts Count*

Subsystems Core Competencies

Thermal Energy Management



- •Components
- •Design Assessment

Air Base Technology

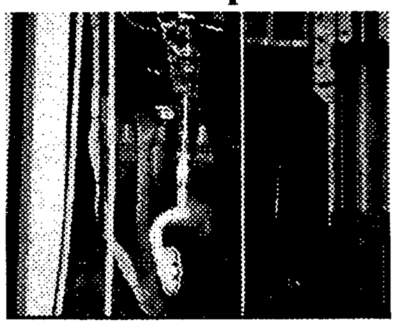
- •Fire Fighting Technology
- •Energy Technology
- •Pavement & Facilities

Critical Components

Aircrew Safety

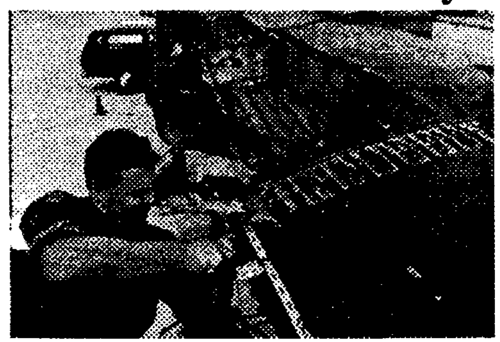
- •Transparencies
- •Precision Aerial Delivery

Ground Operations



- •Landing Gear Systems

Aircraft Survivability

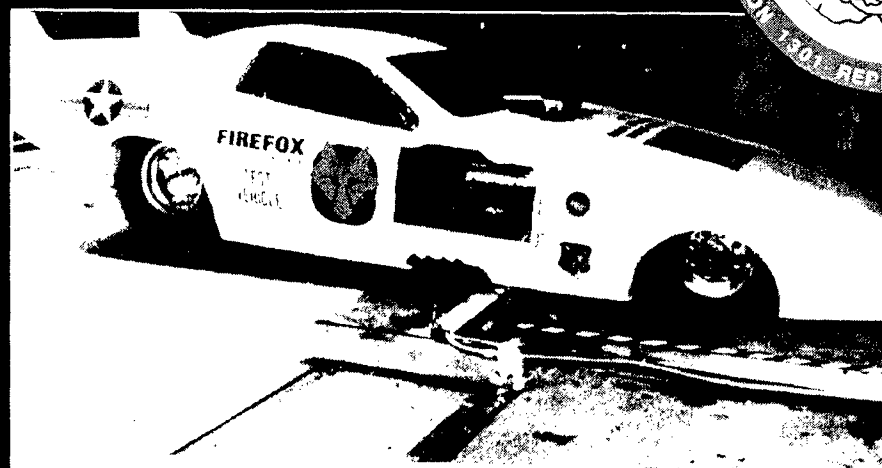


- •Fire Suppression
- •Aircraft Battle Damage Repair
- •Combat Damage Reduction

DOD Fire Protection Technology

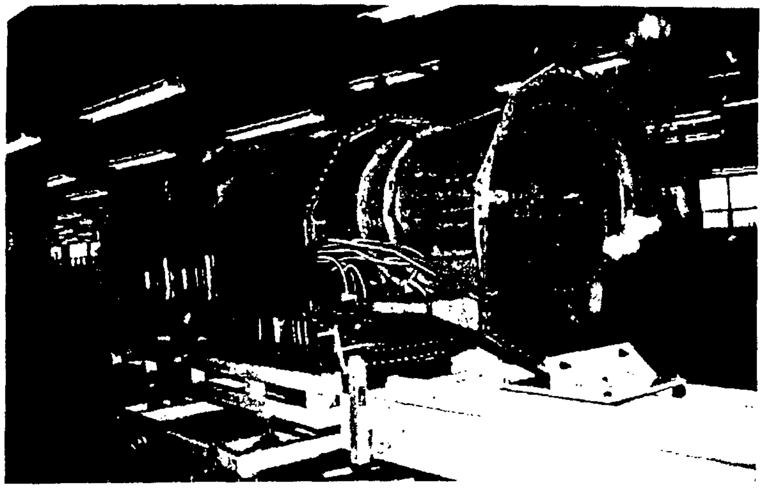
- Goal: Find environmentally friendly alternative to banned Halon 1301 fire suppression chemicals
- Benefits to AF and others:
  - Validated and quantified replacement to Halon 1301 for military aircraft
  - Elimination DOD dependence on Halon 1301 for fire protection
  - Solution transferable to FAA, and others (i.e. Automotive)
  - Follow up work to be fielded by F-22, C-17 and F-16
  - Compliance with current and future EPA standards

Halon Protects Aircraft from fire



Halon is also used in other applications

WL/FIVS FIRE PROTECTION



Engine Nacelle Fire Test Fixture

Dry Bay Fire Test Fixture

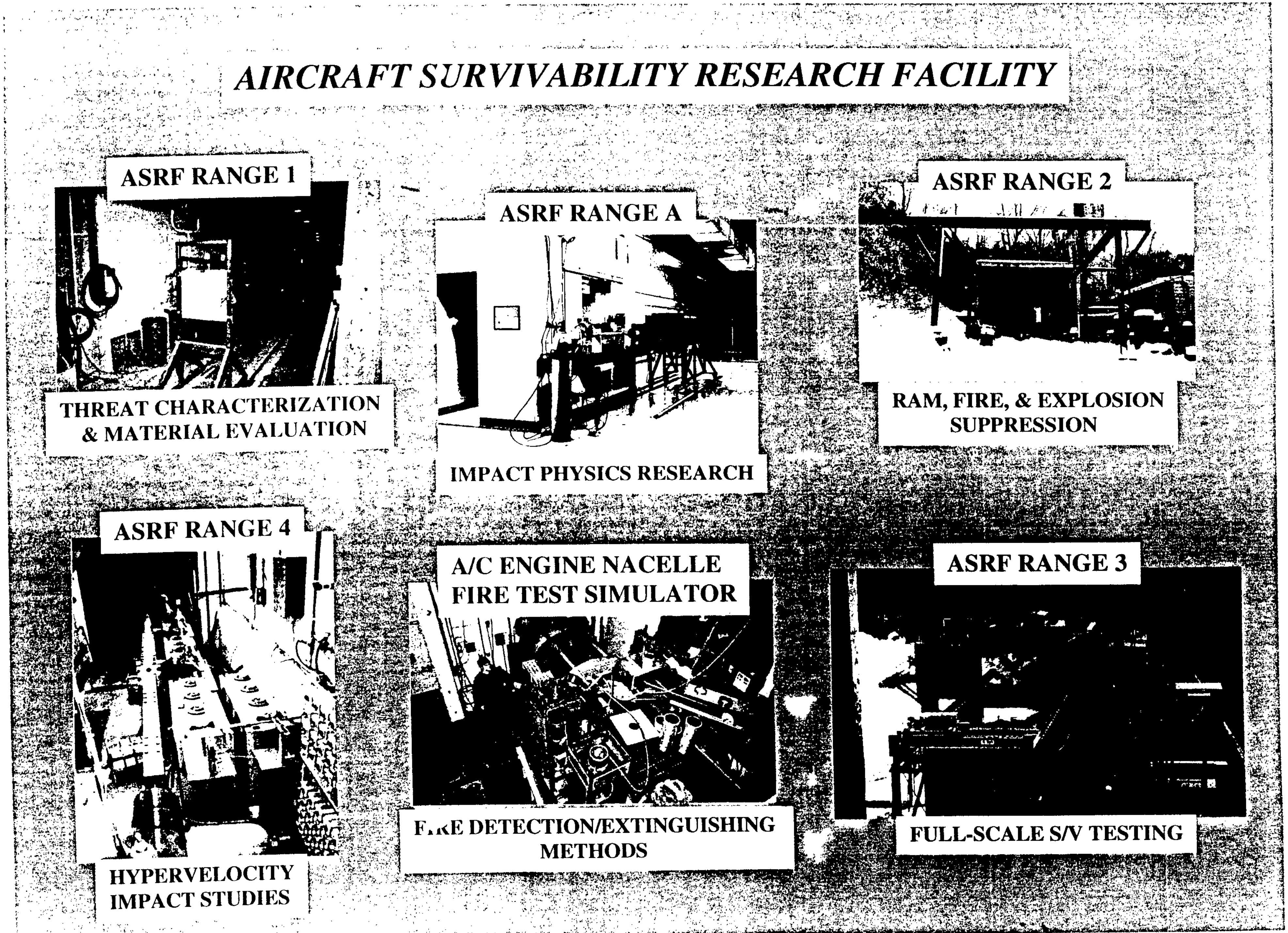
- CUSTOMERS
  - ACC: F-22, F-16, JSF
  - AMC: C-17, C-130
- PARTNERS
  - JTCG/AS
  - NAVY
  - FAA
  - NIST (Next Generation Program)
  - INDUSTRY: Boeing, Walter Kidde, BAH
- PRODUCTS
  - HFC-125 Design Equations
    - -- Engine Nacelles and Dry Bays
  - **Gas Generator Design Guidance for Engine Nacelles**
  - Fire Protection Life Cycle Cost Model
  - Engine Nacelle Fire Model
  - Fuel Tank Inerting Technologies

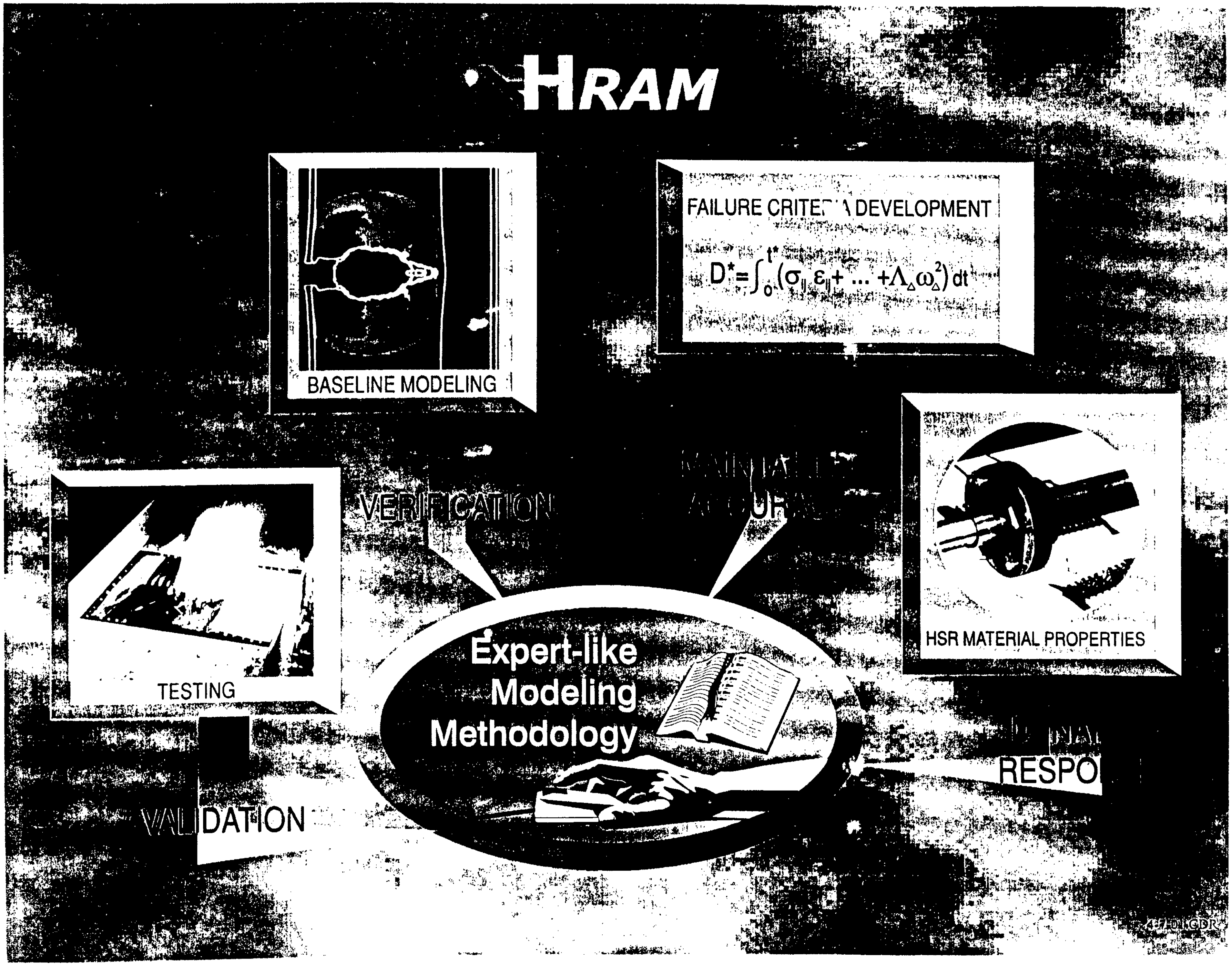
Advanced Combat Maintenance Technology
Advanced Development Program

Developing proven assessment and repair concepts for rapidly returning battle damaged aircraft to an operational status

Advanced Technology Products:

- **Repair of Advanced Structures**
- **Computerized Wiring Maintenance Aid**
- **Transparency Repair System**


AIRCRAFT SURVIVABILITY RESEARCH FACILITY
ASRF RANGE 1
THREAT CHARACTERIZATION & MATERIAL EVALUATION
ASRF RANGE A
IMPACT PHYSICS RESEARCH
ASRF RANGE 2
RAM, FIRE, & EXPLOSION SUPPRESSION
ASRF RANGE 4
HYPERVELOCITY IMPACT STUDIES
A/C ENGINE NACELLE FIRE TEST SIMULATOR
F.RE DETECTION/EXTINGUISHING METHODS
ASRF RANGE 3
FULL-SCALE S/V TESTING


HRAM
BASELINE MODELING
FAILURE CRITE' A DEVELOPMENT
$D^* = \int_0^{t^*} (\sigma_{ij}\varepsilon_{ij} + \ldots + \Lambda_\Delta \omega_\Delta^2)\,dt$
VERIFICATION
HSR MATERIAL PROPERTIES
TESTING
Expert-like Modeling Methodology
RESPO
VALIDATION

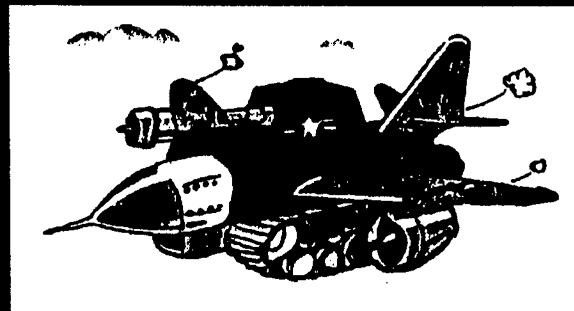
METHODOLOGY IMPROVEMENTS

CODES

CURRENT

- Little V&V
- Poor understanding of phenomena
- Poor database
- Worst-case or nonexisting requirements

Over/Under Design



THE FUTURE

- Validated
- Physics based
- Good database
- Realistic requirements

Optimal Design


Propulsion Controlled Aircraft: A Safety and Survivability Enhancement Concept
Frank W. (Bill) Burcham
NASA Dryden Flight Research Center
ADPA/NSIA Symposium
Enhancing Aircraft Survivability

Propulsion Controlled Aircraft: A Safety and Survivability Enhancement Concept

Frank W. Burcham, Jr, and Joel Sitz, NASA Dryden Flight Research Center

John Bull, Caelum Corporation, NASA Ames Research Center

Paper for the American Defense Preparedness Symposium on Enhancing Aircraft Survivability, Oct 21-23, 1997, Naval Post Graduate School

Modern aircraft with today's advanced technology have achieved an astounding safety record. However, as the number of operations continues to increase, we need to continue to examine methods to survive extremely unlikely failure scenarios. Triggered by the Sioux City accident, we at NASA Dryden have been looking at flying airplanes that have lost all flight controls. Such a loss could occur not only from battle damage, but from uncontained engine failure, mid-air collision, terrorist bomb or missile, structural failure and control system failure.

Flight control using only manual throttle control has been extensively studied. Our results substantiate the experience of The flight 232 crew; that manual throttle control landings range from very difficult to impossible, depending on the aircraft configuration. NASA Dryden developed what came to be called the Propulsion Controlled Aircraft or PCA system, using computerized control of engine thrust, and, with PCA, safe landings are possible for many airplanes. Flight tests of an F-15 and an MD-11 have demonstrated landings without the use of any of the normal flight controls. In addition, a PCA system was developed at NASA Ames and has been proven on a high fidelity simulation of the B-747. and by Boeing on a C-17 simulation have also shown safe landing capability.

These PCA systems used full authority control of the engines, and thus would require digital engine controls and modifications to the engine control software. In the new NASA spirit, we looked at Faster - Cheaper and maybe good enough variations on the PCA theme. Pitch control may be adequately provided by driving the engines through the autothrottle system that exisits on many of today's airplanes. On the B-747-400, using the autothrottle system and the existing 5% digital engine trim capability, safe landings could still be made. We call this PCA-Lite. It worked well in turbulence levels to light-to-moderate and crosswinds to 10 knots.

For airplanes with autothrottles but without digital engine controls, we looked at whether the pilot could manually manipulate the throttles to provide the differential thrust for lateral control. On the B-747 simulator, the answer was clearly yes; this became "PCA Ultra-lite". On the MD-11

simulator, with the engines more inboard, results were not as good...the landing were probably all survivable, but it was very difficult to land on the runway because of the sluggish lateral control capability with manual thrust control. This concept is just starting to evolve, and more airplanes need to be examined.

For the really-really-really bad day where you lose flight controls and also lose a wing engine, if only the engine or engines on one wing were still operating, would there be any possibility of providing emergency flight control? In response to this potential situation, NASA Dryden has taken a first look at a concept that shows that one engine can provide limited flight control capability if the lateral center of gravity (CGY) can be shifted toward the side of the airplane that has the operating engine. Limited simulation tests with all conventional flight controls inoperative and a wing engine inoperative on the MD-11 have shown positive flight control capability within the available range of lateral CG offset. On 4-engine airplanes, simulations of the B-720 at NASA Dryden, and the B-747 at NASA Ames, have also shown positive control capability within the available range of CGY offset.

Overall, the response of engines as flight controllers has been adequate. Transport engines are slower to respond, but those airplanes also have slower dynamics; the net result has been that engine response has been fast enough to damp aircraft dynamics. There have been cases where the thrust level was near idle and engine response became very slow, particularly for landings with no flaps. Shallower glideslope approaches helped this problem.

In summary, engine thrust can be used for airplane flight control. Manual thrust control is OK for continuing flight, but is not adequate for landing. A system that uses computer-controlled thrust has been shown to provide safe landing capability for fighter and transport airplanes. Simplified versions of this PCA system have also been studied recently, and also show promise for emergency landings.

WHY Throttles-Only Control Research?

NASA
FWB 92-53f

Numerous aircraft accidents caused by loss of primary flight control system

- **JAL B-747 in Japan** hyd, struc fail
- **UAL DC-10, Sioux City** hyd, engine fail
- **C-5 Vietnam** hyd, struc fail
- **F-18, Indiana** hyd leak
- **F-18, Japan** FCS LVDT failure
- **Turkish DC-10 at Paris** Cables, baggage door
- **B-52H, Patterson, AFB** hyd leak
- **F-14 #1, Long Island** hyd leak
- **XB-70, Edwards** lost vertical/rudders, mid-air
- **18% of SEA (Vietnam) losses** Various

Other incidents were not accidents because of exceptional crew skill

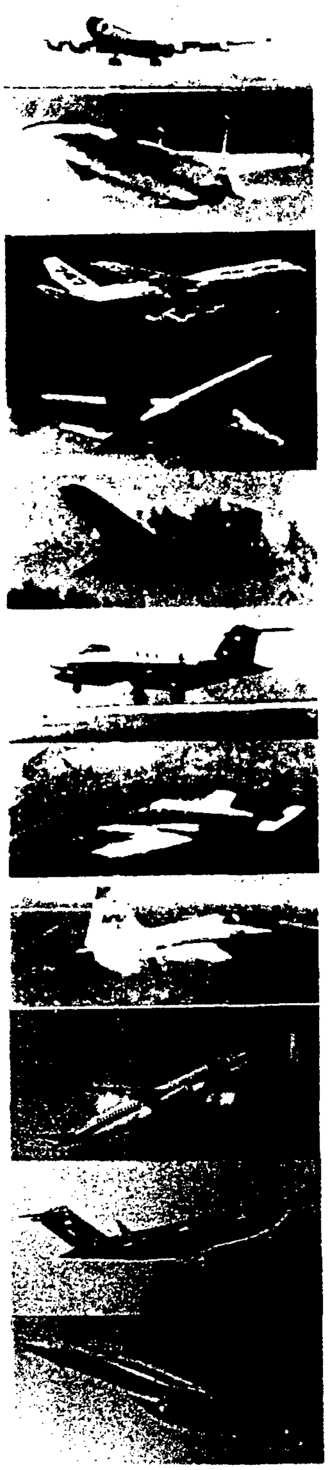
- **A-10 Desert Storm** AAA/Cables
- **Delta L-1011 at LAX** Jammed stab
- **B-52G, Robbins AFB** hyd leak

NTSB Recommendation from the UA232 accident:

"Encourage research and development of backup flight control systems for newly certified wide-body airplanes that utilize an *alternate source of motive power* separate from that source used for the conventional control system"

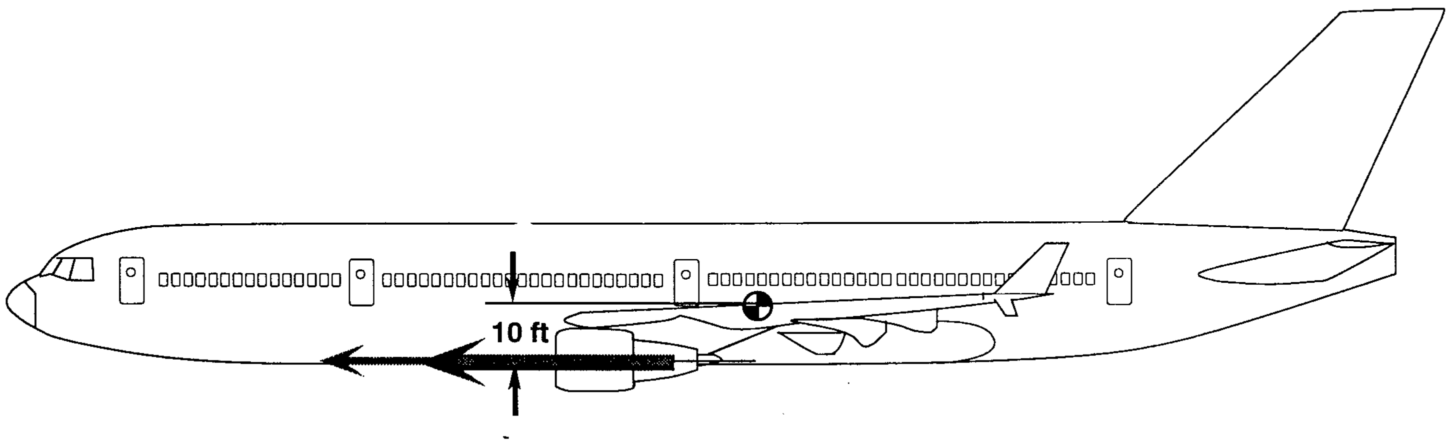
Airplanes Studied

NASA
FWB 92-54c

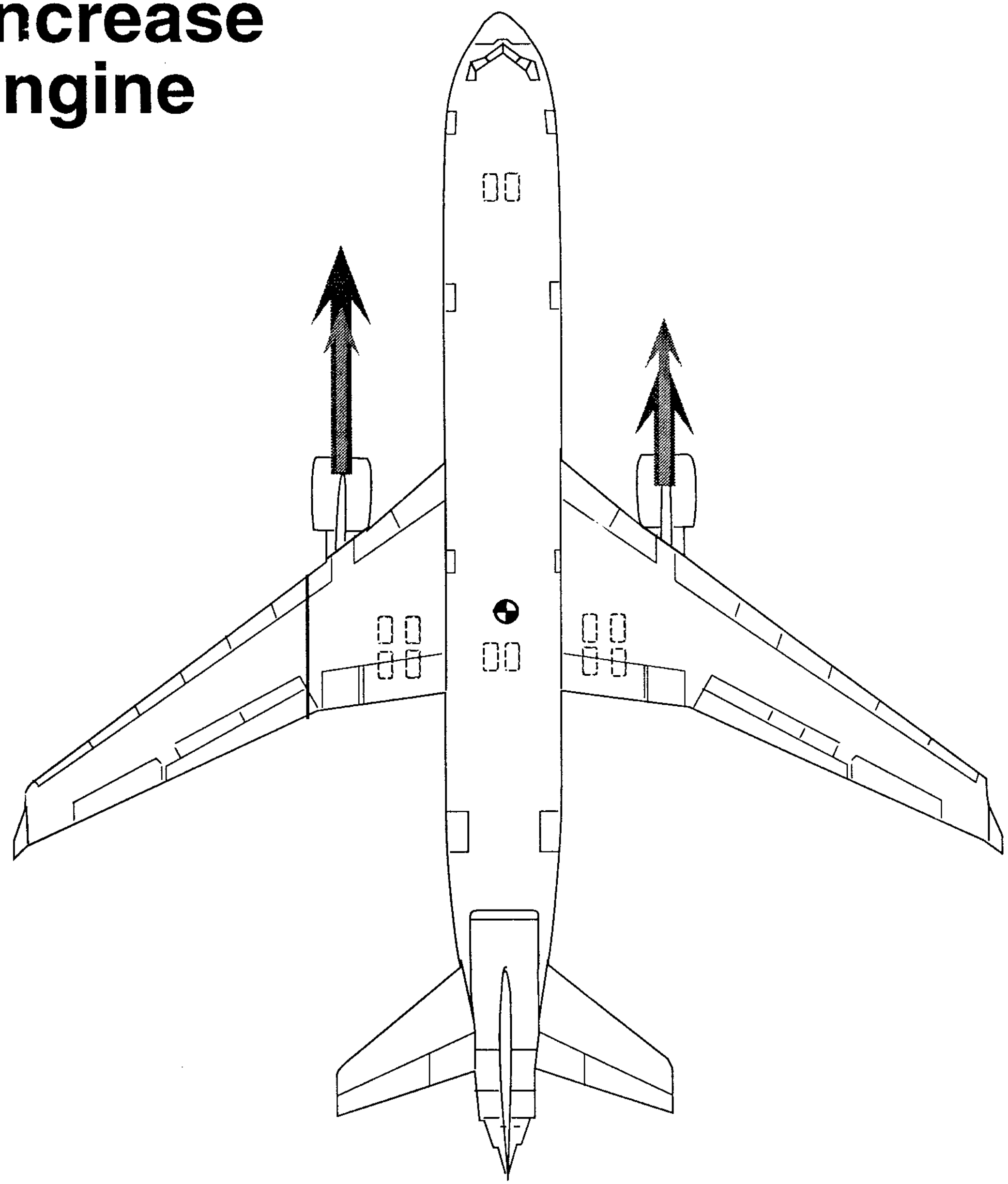


	Simulation	Flight
B-720	●	
F-15	●	●
B-747	●	●
MD-11	●	●
B-727	●	
MD-90	●	
Learjet		●
& T-39		●
PA-30		●
C-402	●	
T-38		●
ACFS Generic Twinjet	●	
C-17	●	●
F-18	●	●

To climb, add thrust on the wing engines



To turn right, increase thrust on left engine



NASA
FWB 96-14

Manual Throttles-Only Control

- Varies greatly from aircraft to aircraft
  -primary factor: engine location
- Very high pilot workload, significant training factor

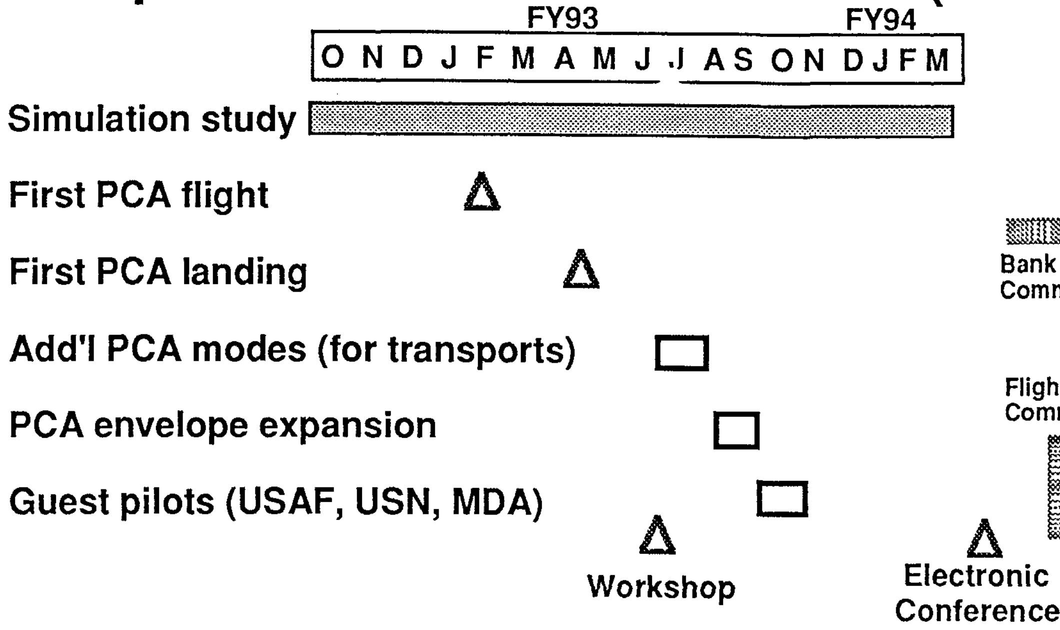
Usually adequate for up and away flight

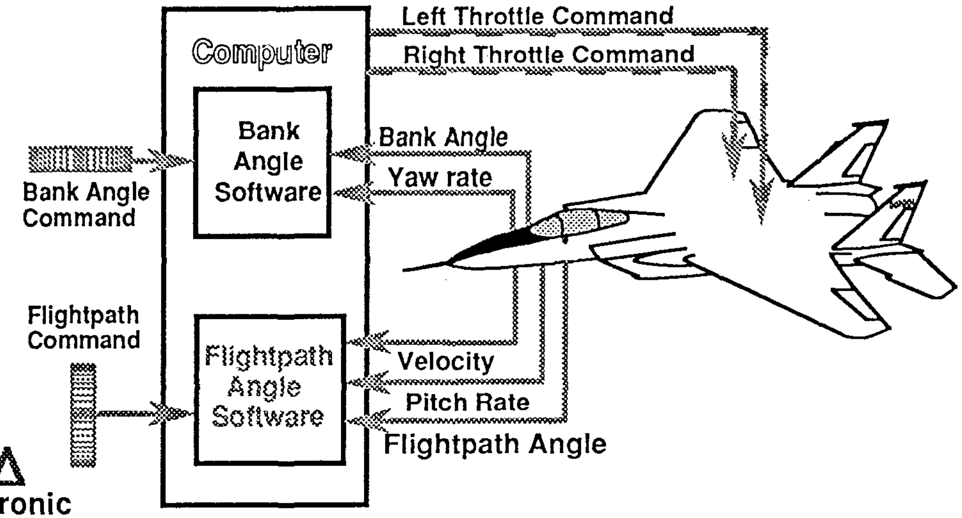
Usually unsatisfactory for safe runway landing

Something else needed for safe runway landings

Propulsion Controlled Aircraft (PCA) - F-15 Results

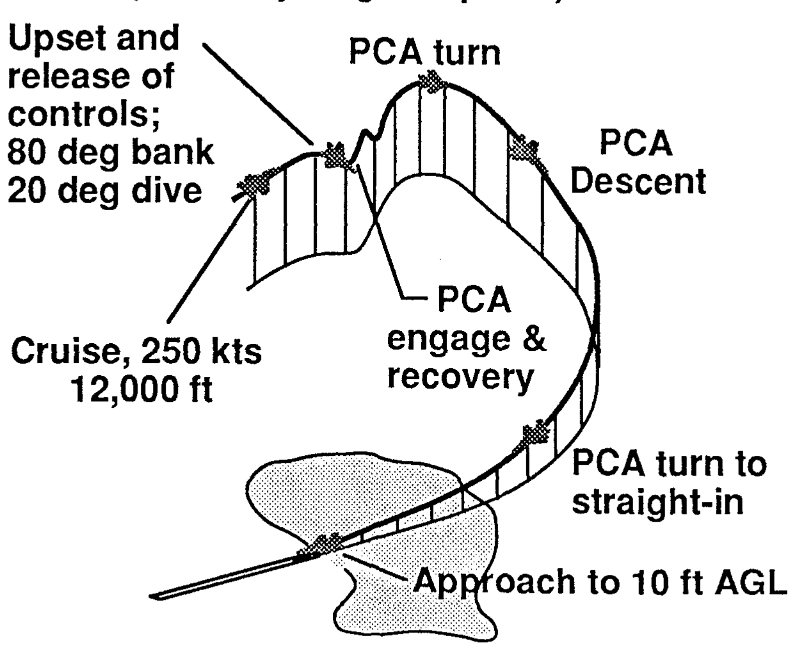
NASA
FWB 94-42



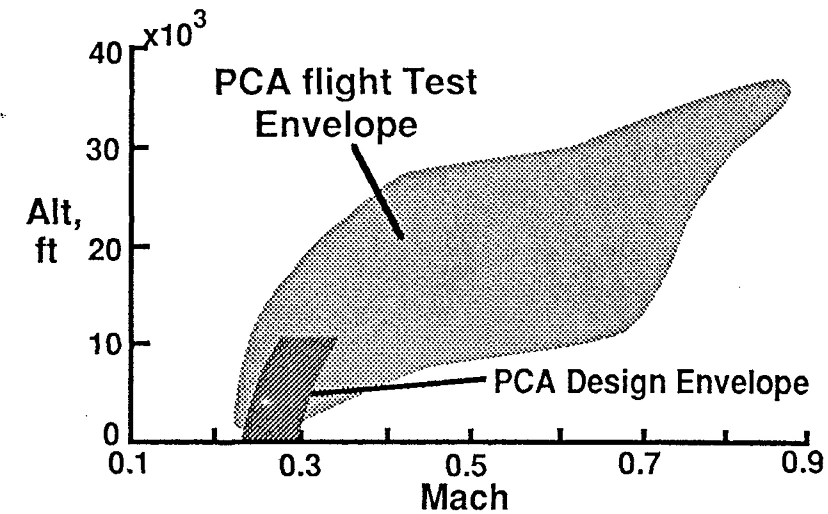


Augmented PCA Block Diagram

Simulated hydraulic failure, PCA recovery, approach to landing
(Flown by all guest pilots)



PCA Design and actual test envelope

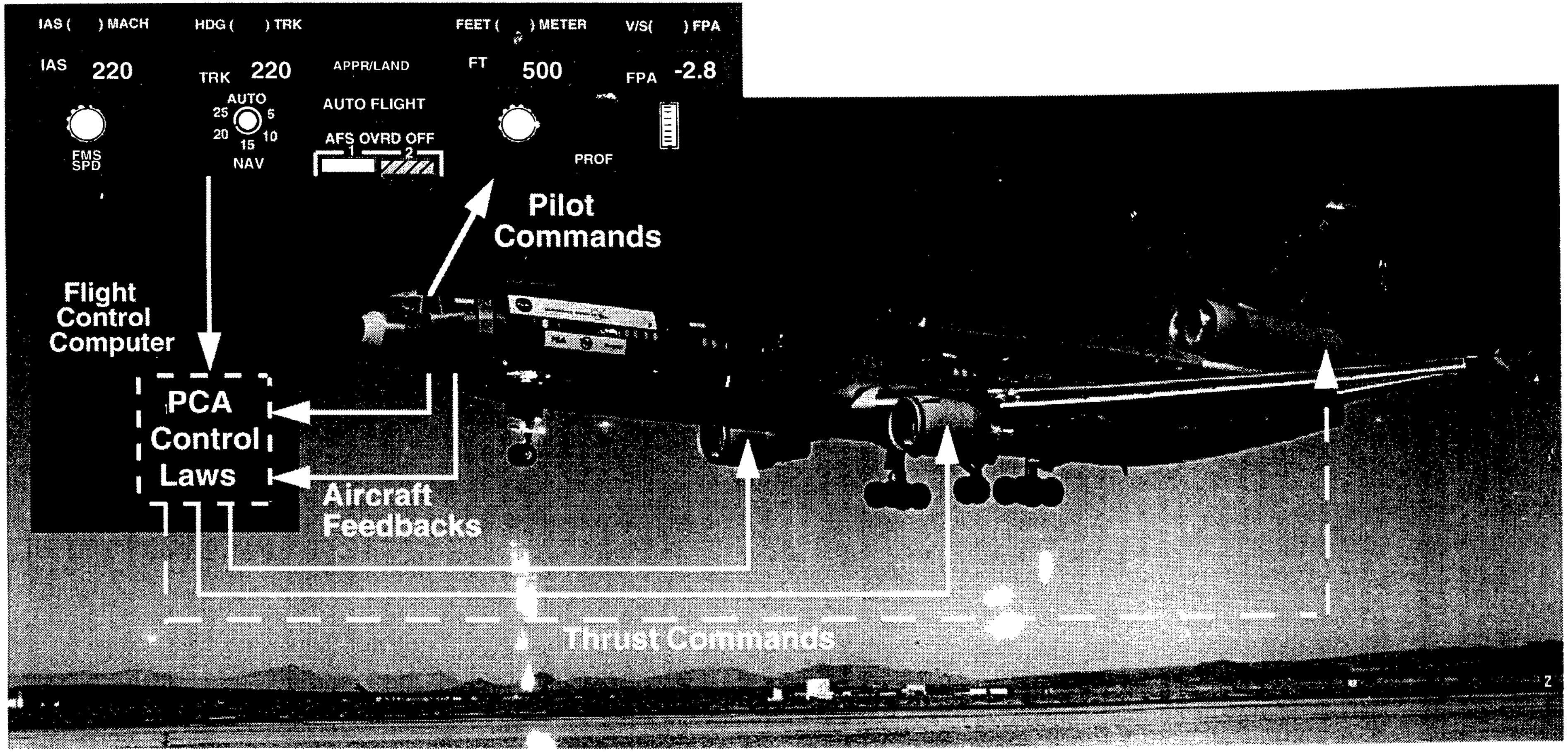


Results: PCA concept proven for backup control for current and future designs

MD-11 Propulsion Controlled Aircraft System

NASA
FWB 97-25

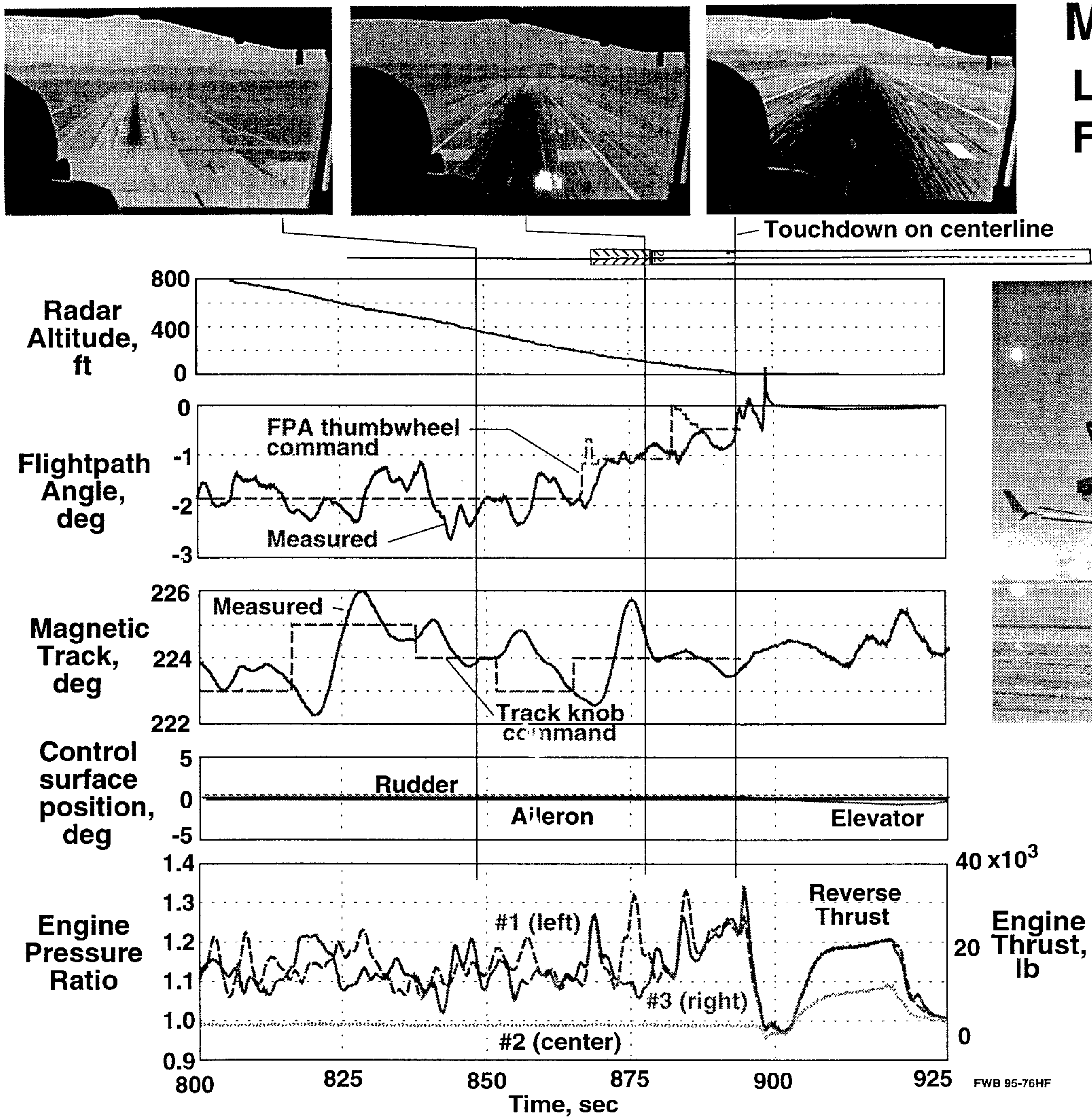
Software changes to existing systems

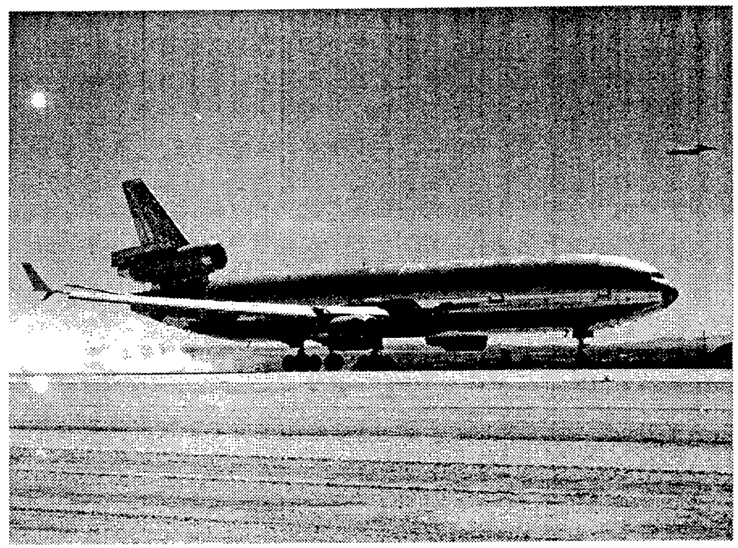


- Safe landings without using any flight controls
- Goals exceeded ahead of schedule and under cost
- Demonstrated to 21 airline, DoD, FAA, Boeing and Airbus pilots

MD-11 PCA Landing

Light turbulence
Flaps 28, 175 kts



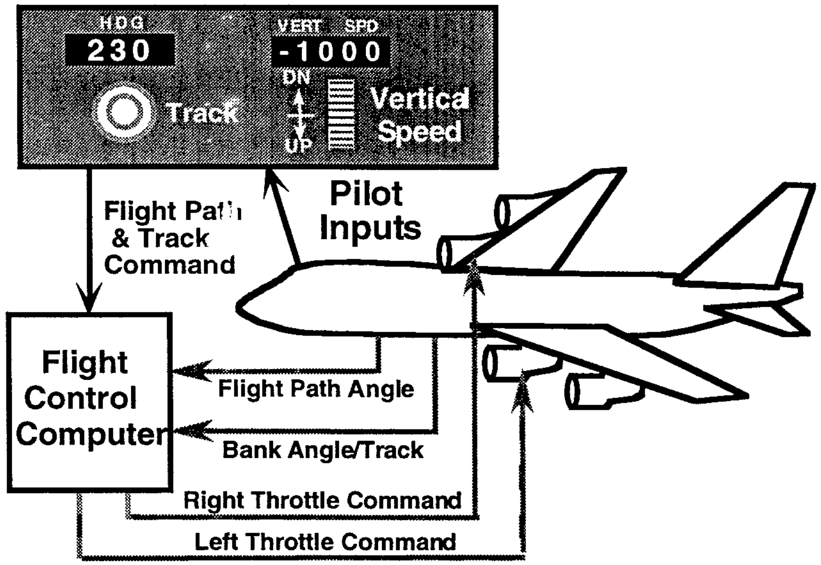


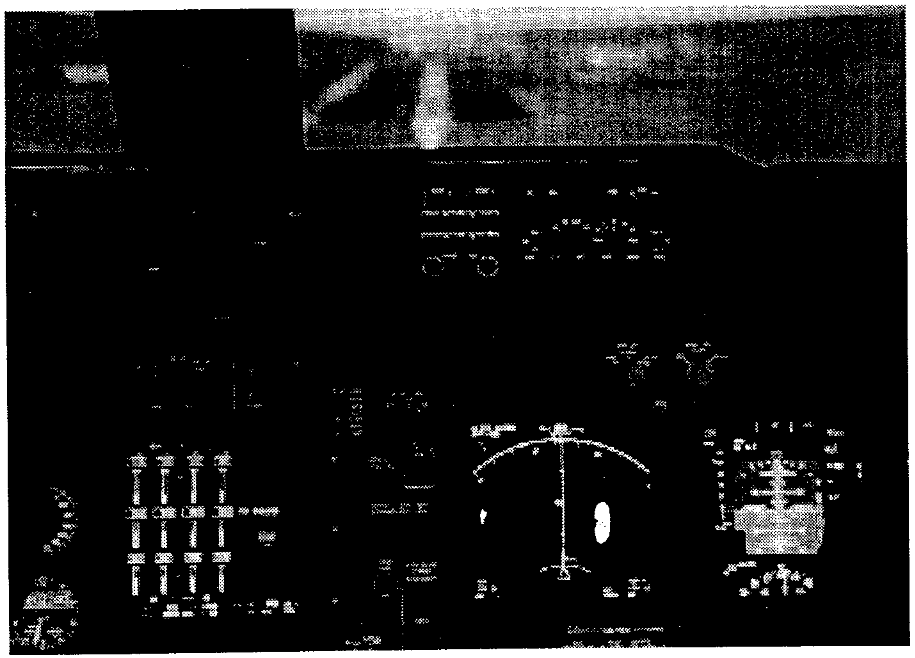
FWB 95-76HF

NASA
FWB 97-14a

Propulsion Controlled Aircraft (PCA) B-747 at Ames

- NASA Ames/FAA Boeing 747 simulator; Level D high fidelity, motion base
- PCA implemented, pilots use existing vertical speed and track knobs
- Also PCA ILS-coupled landing mode
- PCA evaluation by NASA, Boeing USAF & Industry pilots



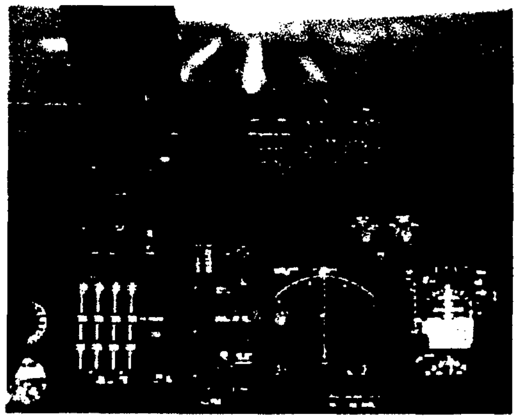


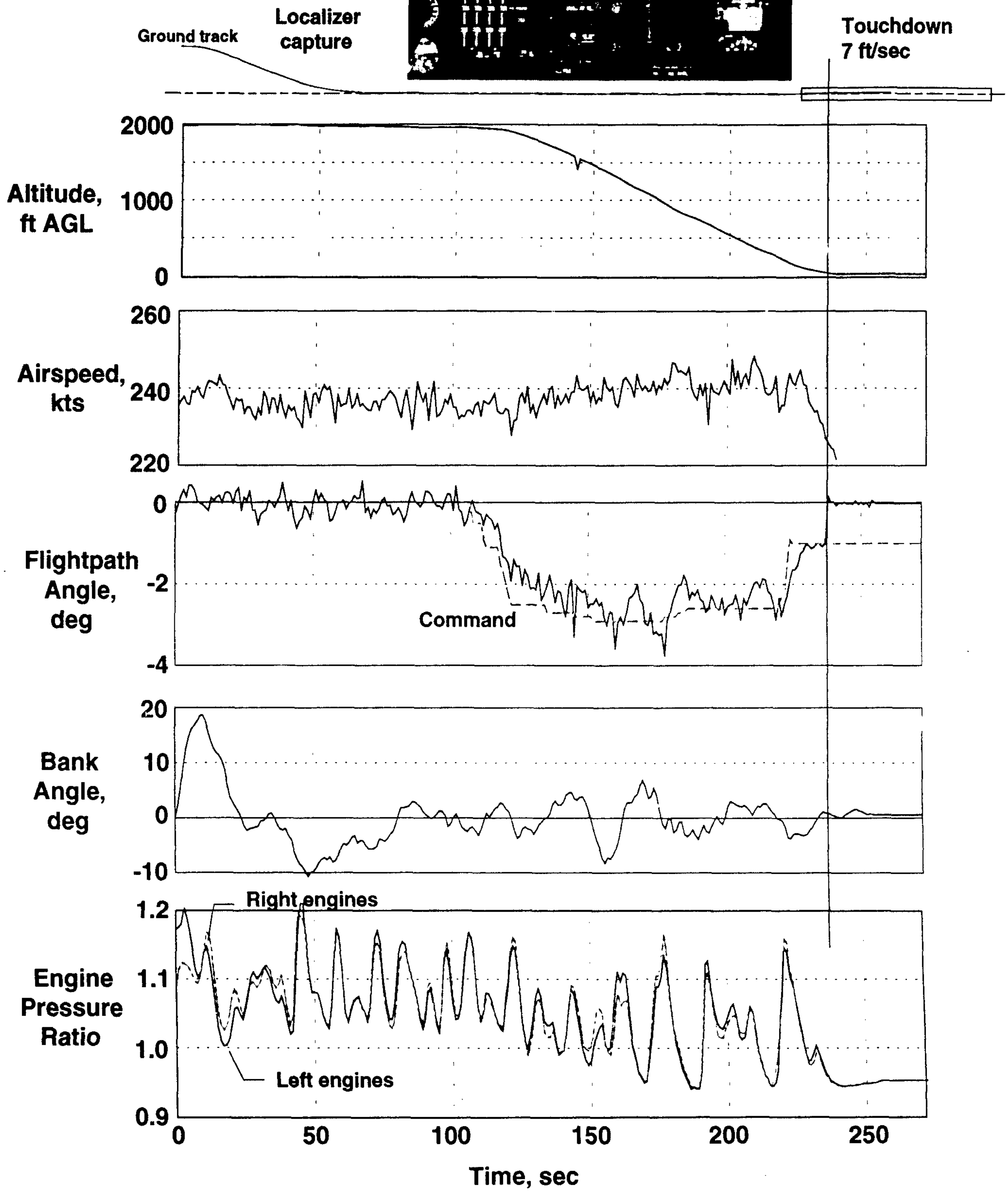
- Tests in 1996 - works very well, similar to MD-11 PCA
- ILS-coupled approach
  - handles higher turbulence levels
  - no crew training required
- Flown by Boeing 747-X chief pilot and Sioux City Flt 232 pilot Dennis Fitch
- Boeing request for aft CG cases tested
- Faster-cheaper PCA concepts tested

B-747 PCA Landing

No hydraulics, no flaps, Localizer-coupled, crosswind and turbulence
Capt. Dennis Fitch, UA 232 pilot, Ames B-747-400 simulator

NASA
FWB 97-07



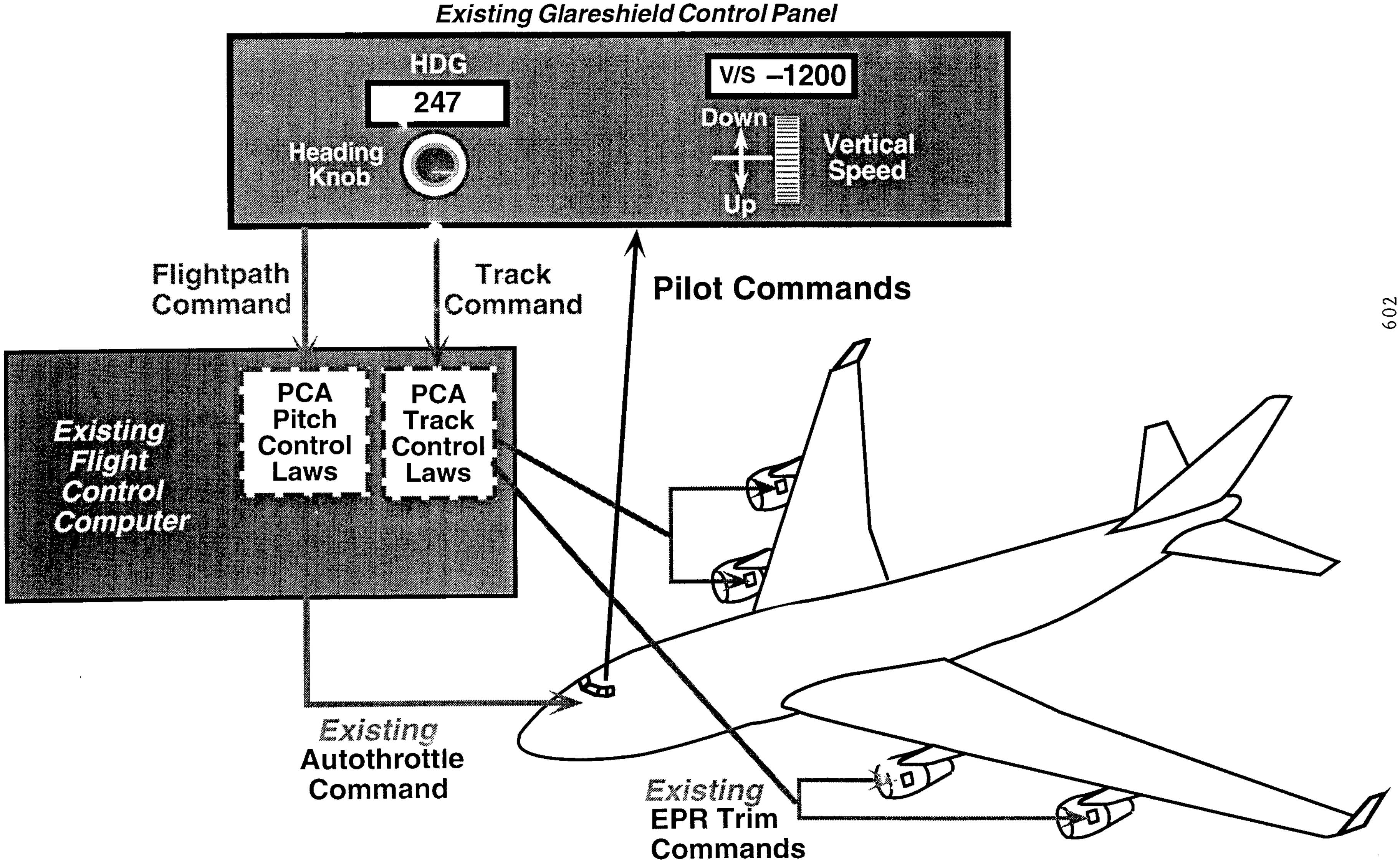


B-747 "PCA Lite"

Faster - Cheaper and Maybe Good Enough PCA

NASA
FWB97-15GL

Uses existing autothrottle loop for pitch control
Uses existing engine trim loop for lateral control

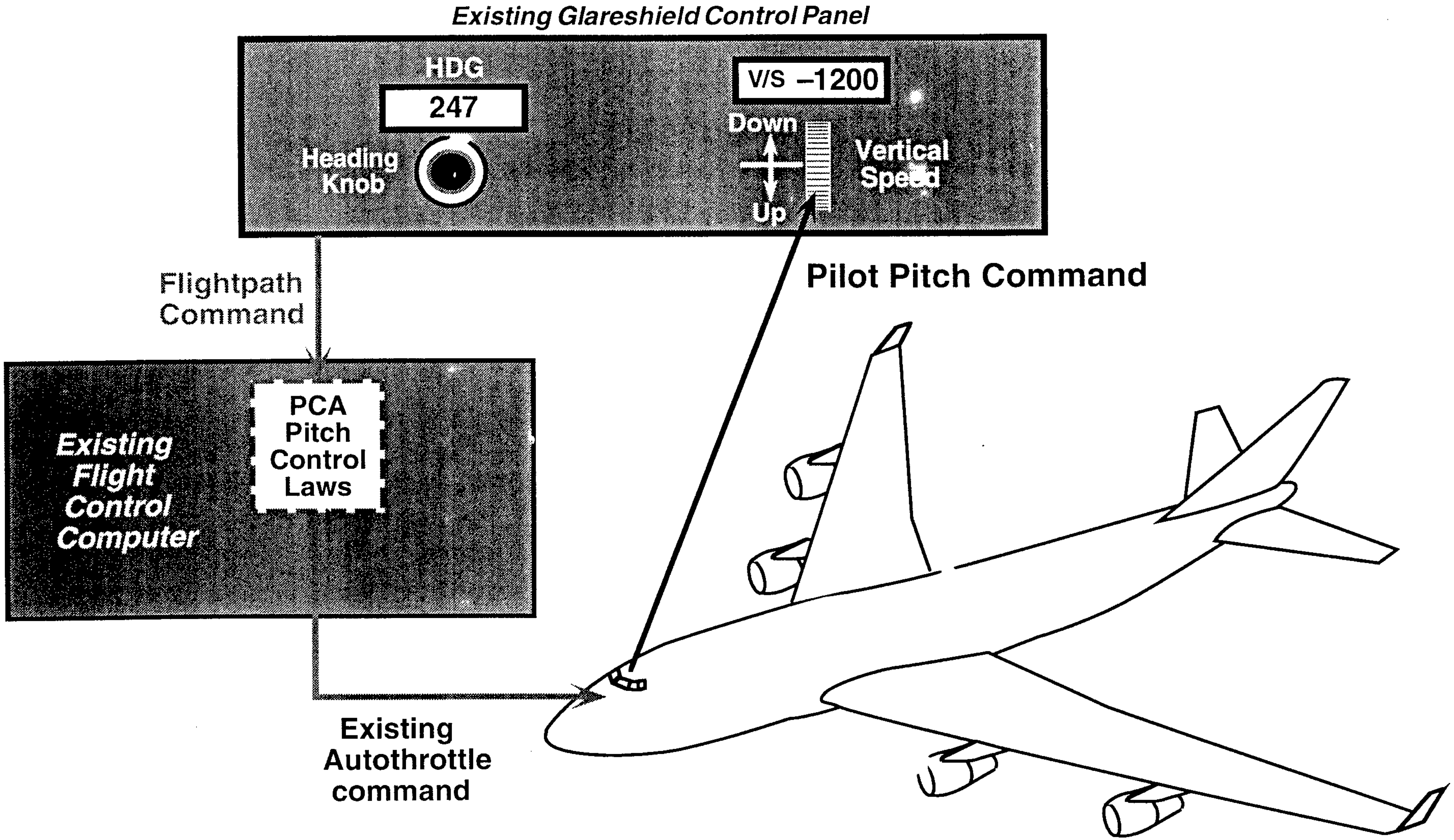


B-747 "PCA Ultra-Lite"

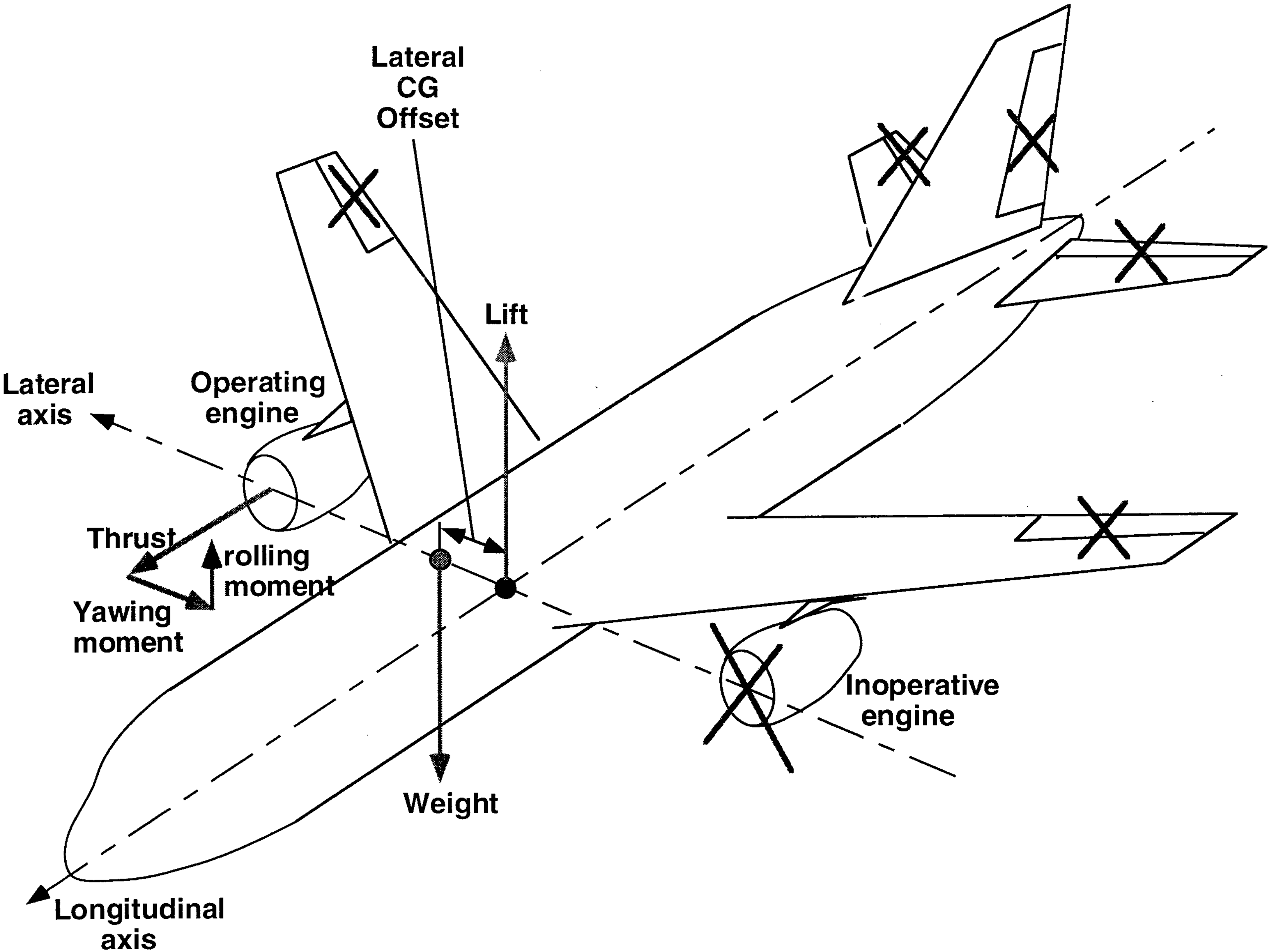
Faster - Cheaper and Maybe Good Enough PCA

NASA
FWB97-15UL

- Uses existing autothrottle loop for pitch control
- Uses pilot manual throttle input for lateral control

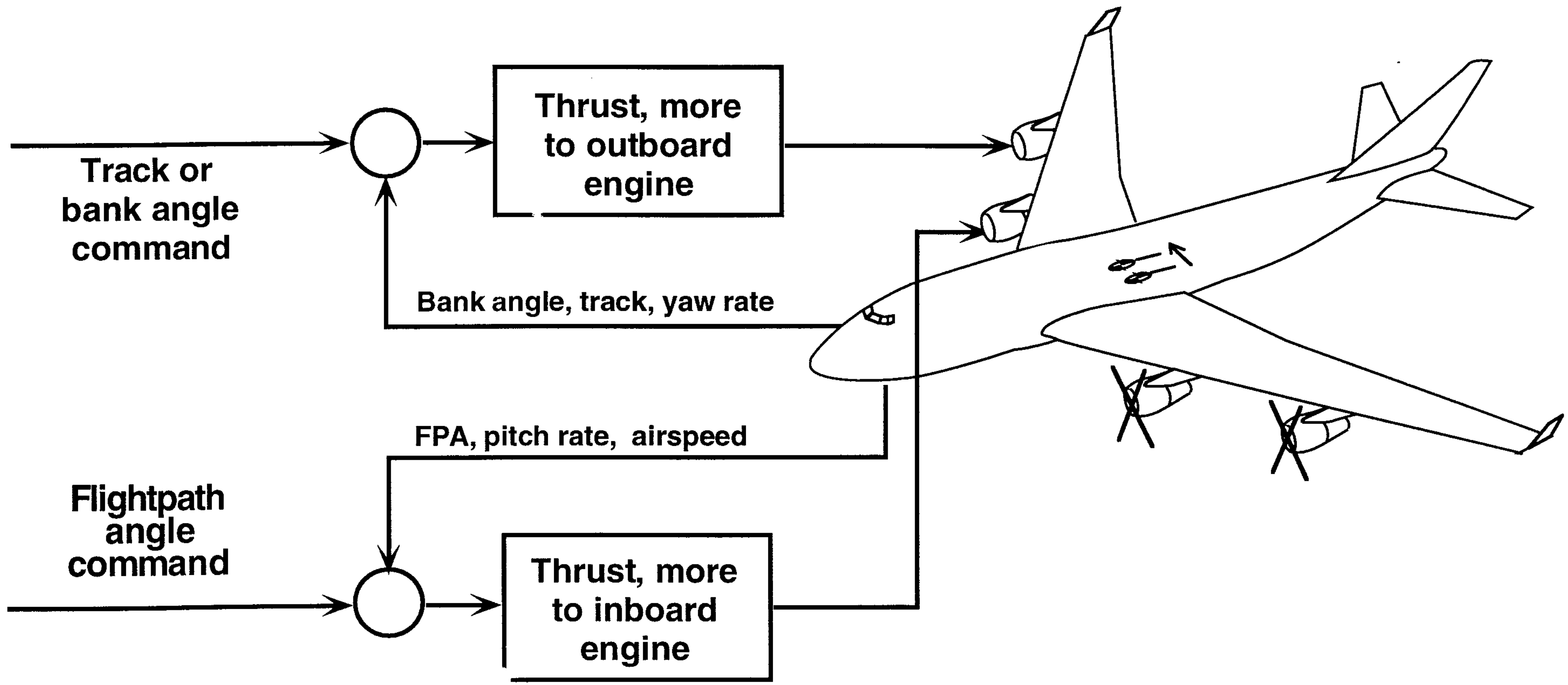


Controls Out, Wing Engine Out and Lateral CG Offset



NASA
FWB 97-56

B-747 Control with Lateral CG Offset
No flight controls, both left engines out
CG shifted to side with good engines



How damage-tolerant is PCA?

NASA
FWB 97-55

Lateral:

Rudder offsets input into simulations to simulate lateral asymmetry

- Control maintained until an engine(s) gets to or near idle power

For approaches on a 2.5° glideslope:

- 5° of rudder on B-747
- 5° of rudder on MD-11 with flaps down
- 4° of rudder on MD-11 with flaps up

Longitudinal:

Trim speed a function of stab setting, CG, and damage

Use CG shift, gear extension, fuel dump, and thrust to change trim speed

Summary

NASA
FWB 97-54

Throttles-Only Control - Manual
- OK for up-and-away flight
- Not adequate for landing

Full PCA System
- Flight tests: Safe landings made in F-15, MD-11
- Simulations: Safe landings in B-747, C-17, B-757

Simplified PCA
- PCA Lite - Works well for B-747
- PCA Ultra-lite - Looks promising

Wing-engine(s)-out – may work with lateral CG transfer

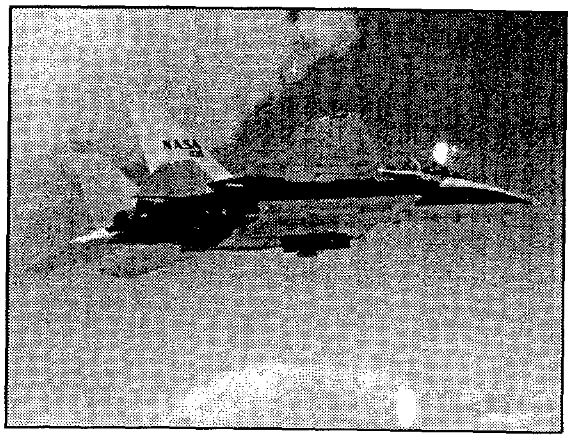
Overall, a promising technique for improving survivability and safety

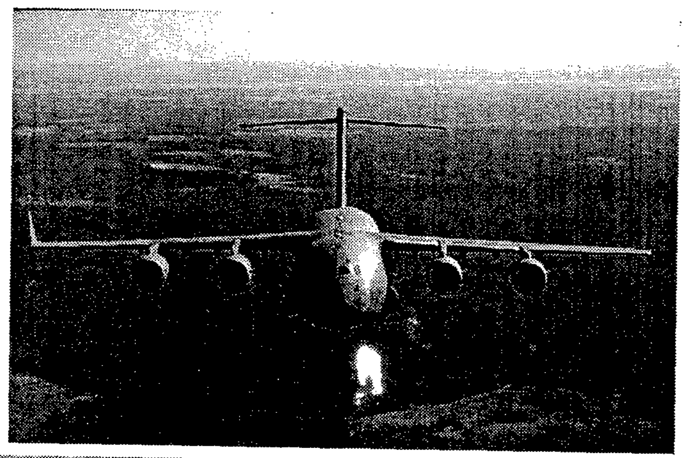
PCA Follow-On Program

NASA, working with other agencies as part of the national safety program, is developing a follow-on system to PCA called Intelligent Damage-Adaptive Control System (IDACS)

IDACS will, using advanced techniques,identify a problem and advise the crew as to needed actions. It may also in a later form, reconfigure the control system to use all remaining control effectors (control surfaces, engines, flaps, CG, etc) to maintain control

NASA, the FAA, USAF, industry and universities are currently planning the IDACS project. Simulation studies are already underway using the C-17 and F/A-18 airplanes as models.





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Rotorcraft Survivability Advancements through Technology

By

Nikolaos Caravasos

Manager, Military Technology

Information, Space, & Defense Systems

Boeing, Philadelphia

Presented at the

American Defense Preparedness Association {ADPA}

National Security Industrial Association {NSIA}

on

Enhancing Aircraft Survivability

A Vulnerability Perspective

Monterey, CA ***23 October 1997***

BOEING®

Nikolaos (Nick) Caravasos

Mr. Caravasos has 36 plus years of aircraft experience with Boeing; 32 plus years in research & development and 4 years in commercial and rotorcraft designs.

Education/Training

University of Pennsylvania	MS in Applied Management
West Virginia University	BS in Engineering
UCLA, Widener, WVU	Graduate and Specialty Courses

Employment History

1984 to Present - Manager, Military Technology, Boeing Philadelphia

- Responsible for management of Military Technology IR&D program
- Technical & Management Support to Boeing's fixed wing & rotary wing products
- Manager of numerous Army. Navy, & JTCG/AS contracts

1965 to 1983 - Boeing Helicopters, Staff Specialist

- Responsible for Survivability on all Boeing Helicopter products
- Marketing support - Supported marketing activities worldwide.

1961 to 1965 - Boeing Helicopters and Boeing Commercial Airplane Senior Engineer

- Responsible for empennage and passenger accommodations designs

Publications/Awards

- Received the highest IR&D score at Boeing Helicopters in 1985, 1986, 1987, & 1988
- Annual lectures on "Aircraft Combat Survivability" and graduate "Helicopter Design" Courses at the Naval Post Graduate School, Monterey, California
- Lectured to Greece's NATO forces at KETA, Glyfada, Athens, Greece
- Presented and published numerous technical papers for ADPA, AIAA, AAAA, and AHS

Affiliations

- AIAA Survivability Committee - Chairman from 1992 to 1994
- Member of JTCG/AS Industry Advisory Committee

Outline

Nitrogen Inflated Ballistic Bladder {NIBB}

Features

- Hydrodynamic Ram
- Crashworthiness
- Explosion/Fire Suppression

Status

- Phase I Cube Tests {MIL-T-27422}
- Video {Ballistic & 65-ft Crash Drop Tests}

Conclusions

Thermoplastics Research

Tailboom Contract & IR&D Summary

- Design, Analysis, Fabrication, & Tests
- IR&D Support
- Video

Conclusions

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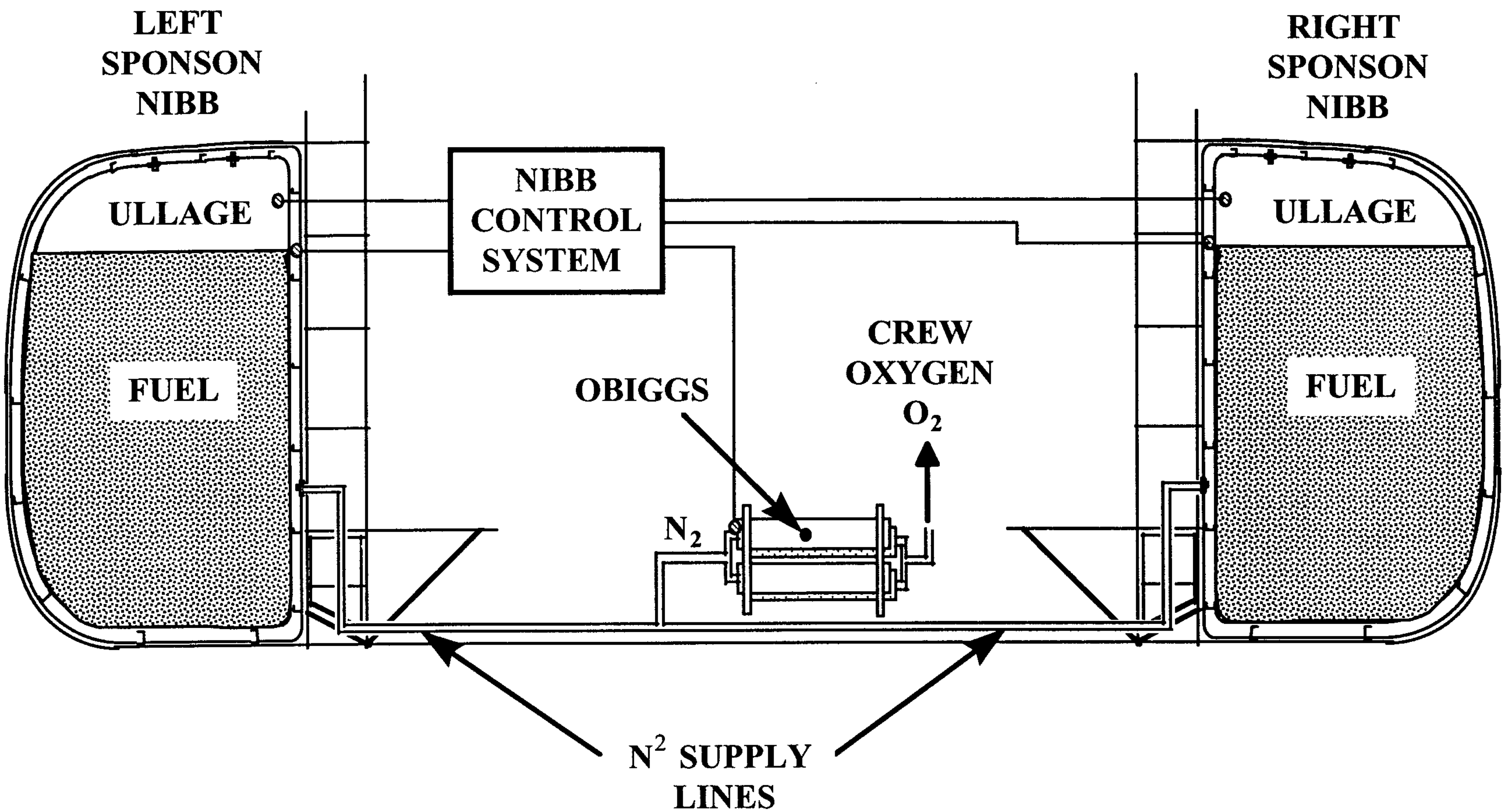
Typical Rotorcraft Fuel System Set-up



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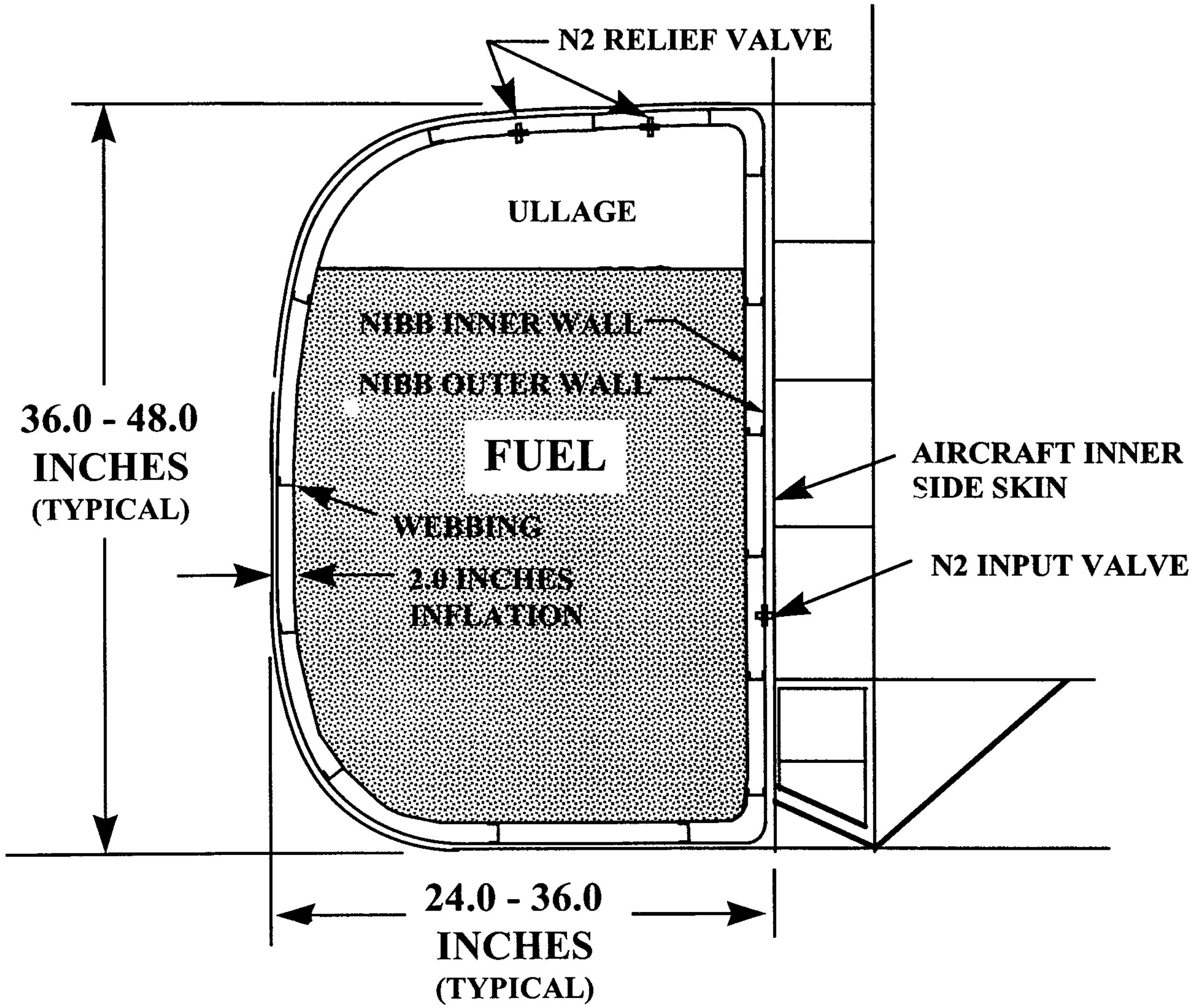
Typical Rotorcraft Fuel Cell



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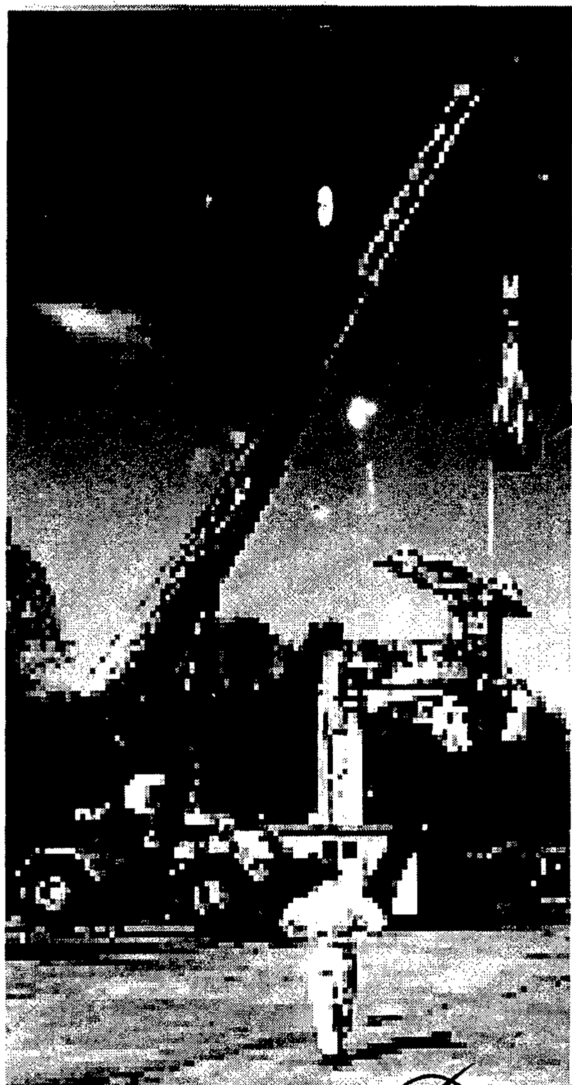
NIBB Cube Testing



Cube Raised to 65-ft Height for Drop Test

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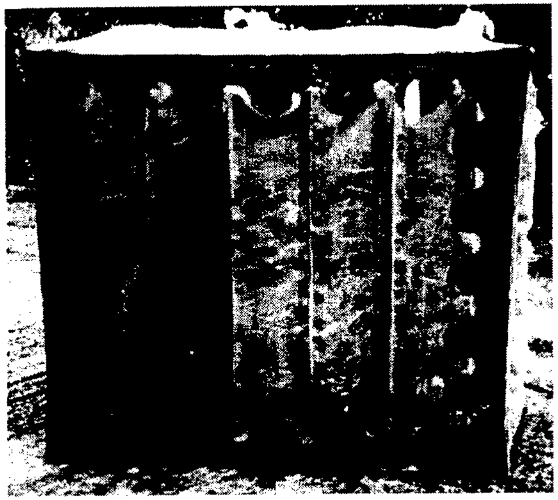
Drop Test Results

No damage to tank walls, seams, or corners

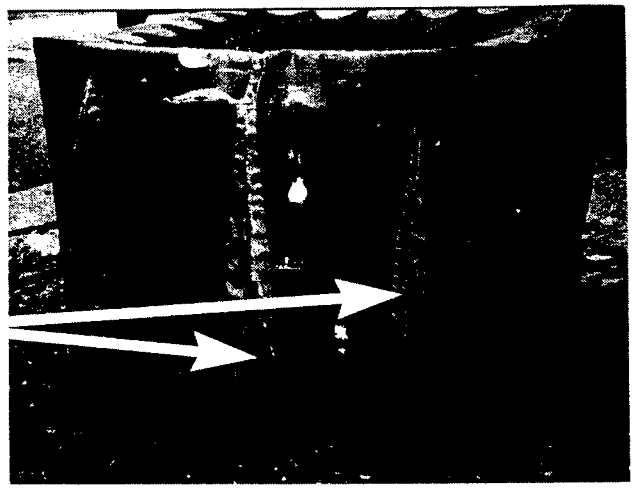


Bottom View

Results of visual inspection

Rubber plugs inside tank detached from tubes allowing water leakage 4 to 5 seconds after impact

Side View



Damage to NIBB outer wall
(This is expected since it is not part of the crashworthiness design)

No leakage during post test air inflation test [0.5 psi]

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Nitrogen Inflated Ballistic Bladder

Conclusions

Where are we?

- *Qualified Concept to Phase I MIL-T-27422 Cube*
  - *Met Drop Test from 65-ft Height*
  - *No damage to surrounding structure from hydrodynamic ram*
  - *Provided self-sealing against 12.7mm tumbled API*

Where do we from here?

- *Phase II Full Scale Qualification*

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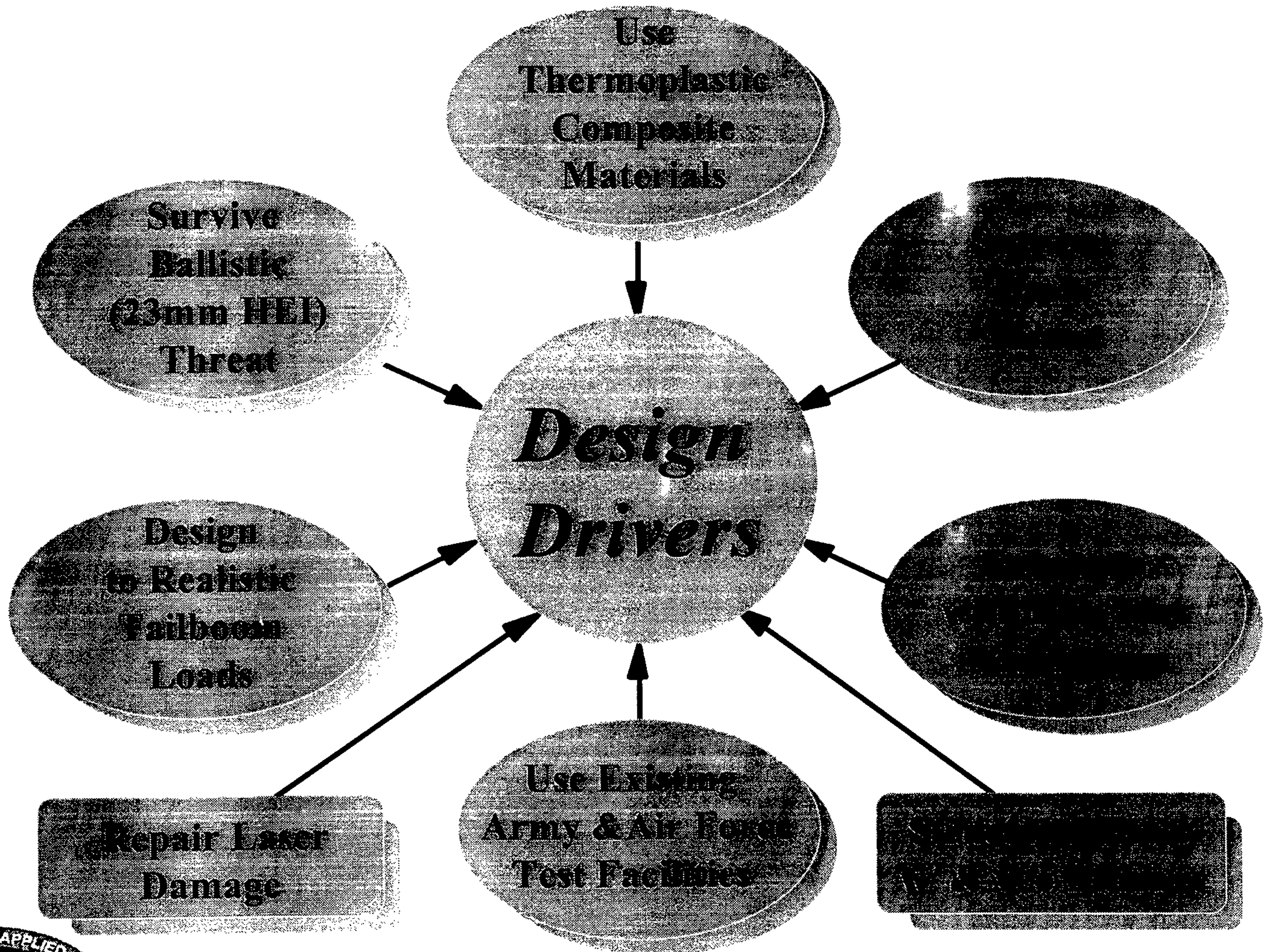
R&D Thermoplastic Tailboom Program

Program Design Drivers



AVIATION APPLIED TECHNOLOGY DIRECTORATE

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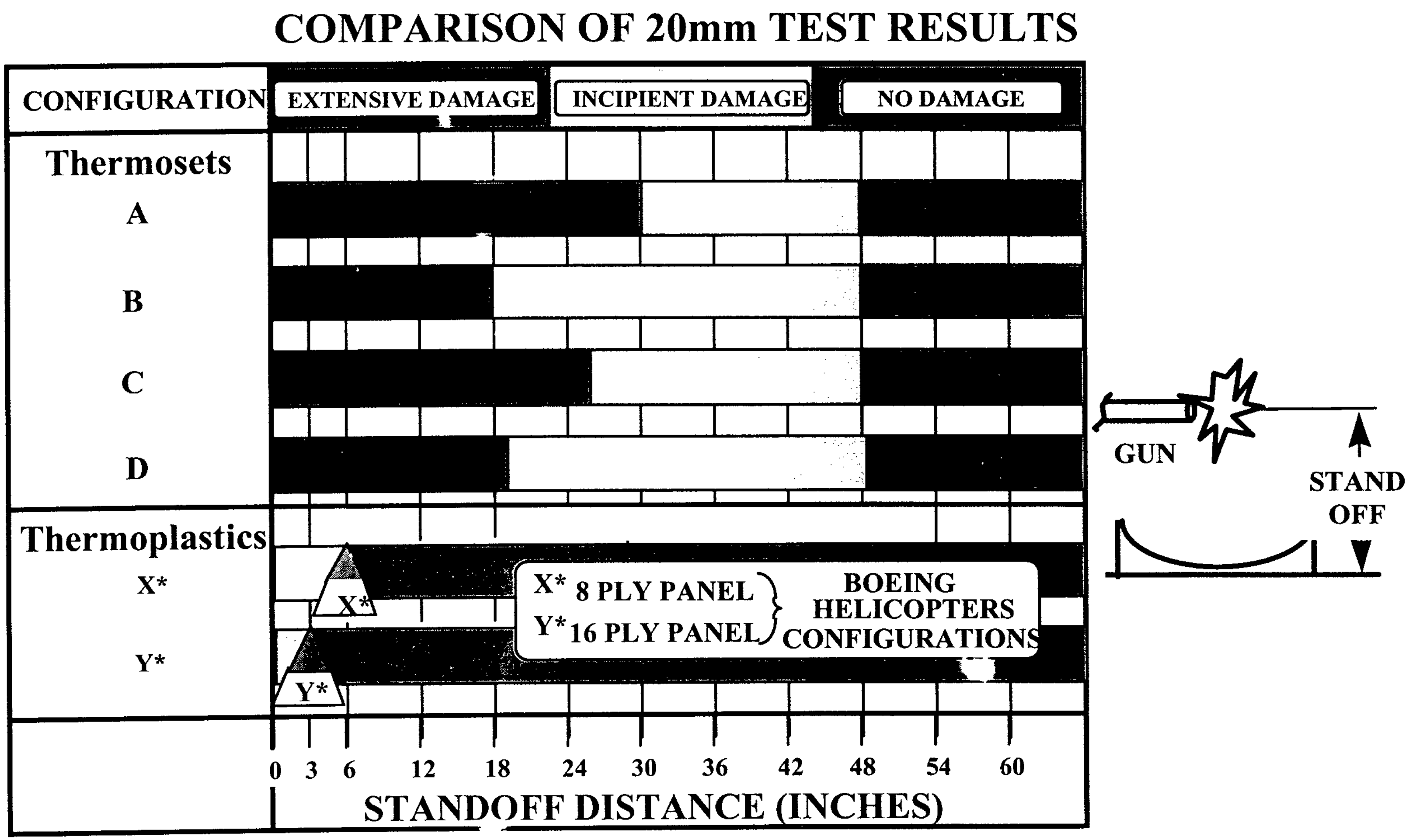
Thermoplastic Panels Survive Blast Pressures

IR&D Program



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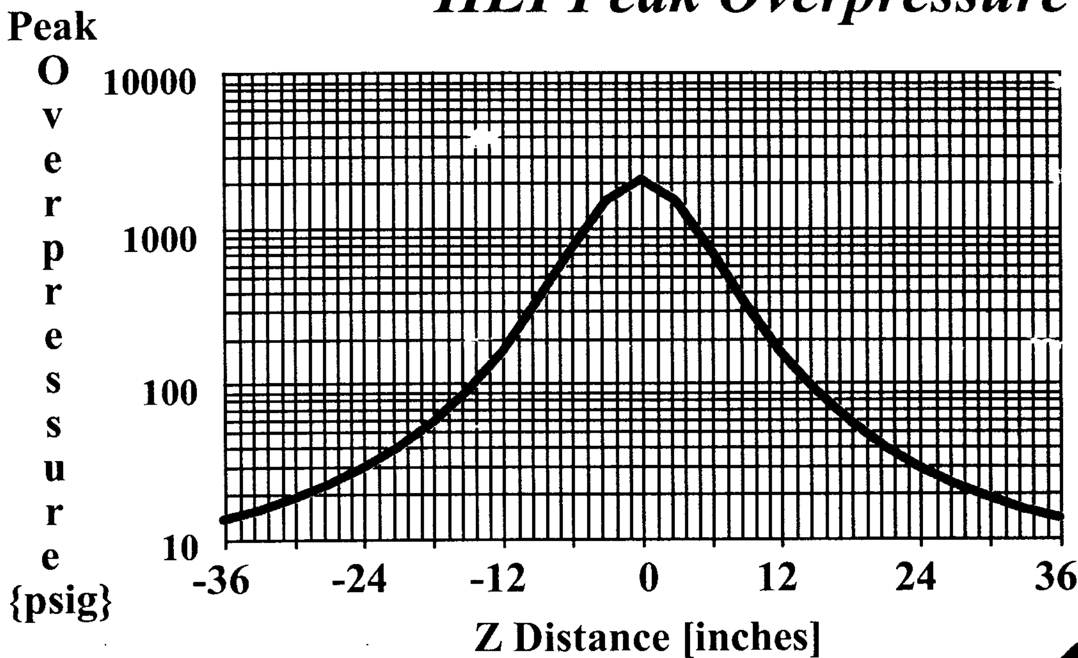
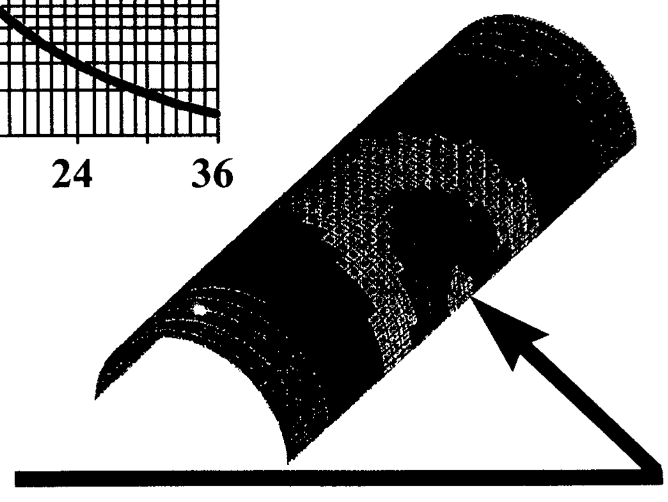
R&D Thermoplastic Tailboom Program

HEI Peak Overpressure

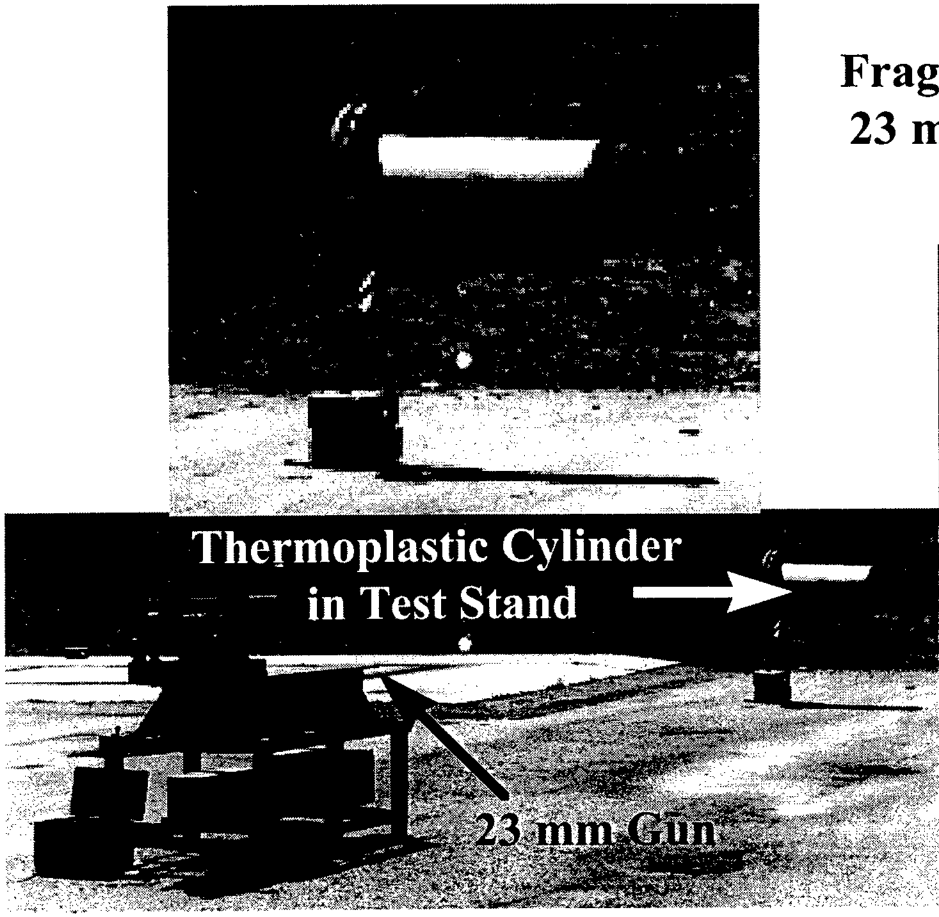


Peak overpressure along longitudinal lines detonating @ 4 to 6 in after penetration

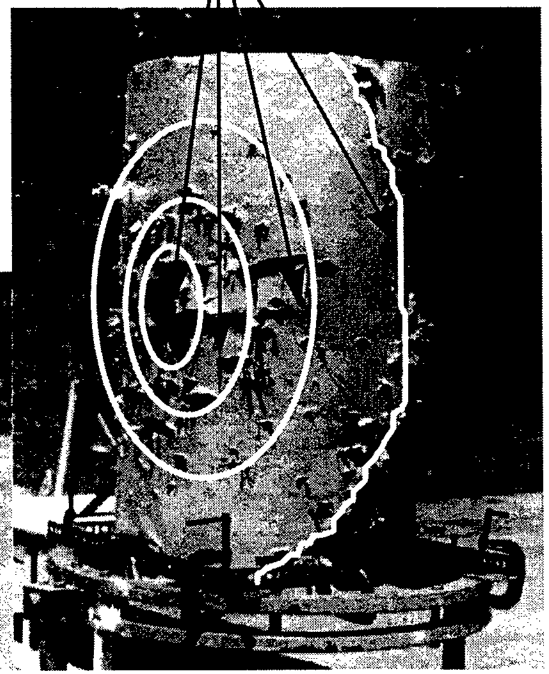


IR&D Thermoplastic Support

Fragmentation Pattern

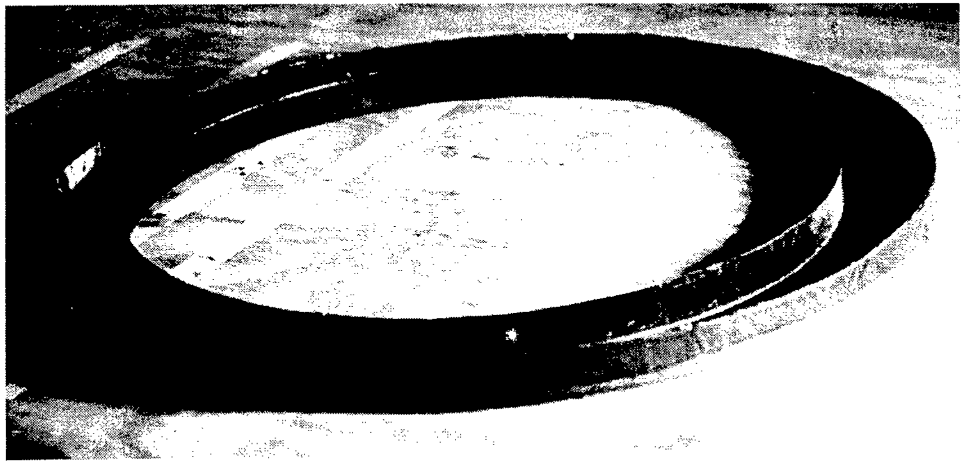


Fragmentation Pattern from
23 mm HEI Delayed Round

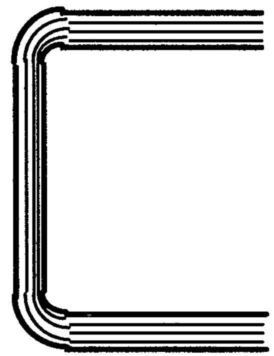


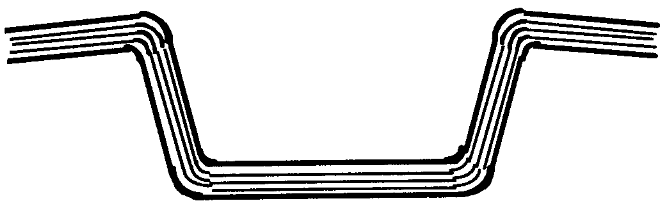
R&D Thermoplastic Tailboom Program

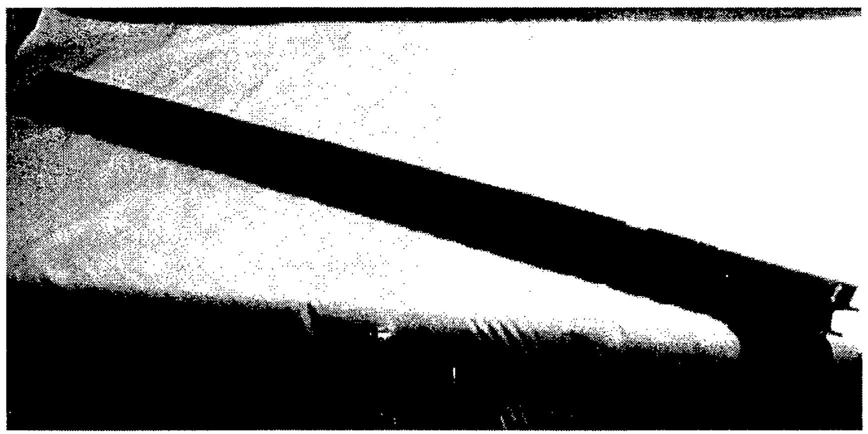
Fabrication - Frames & Longerons



Frame

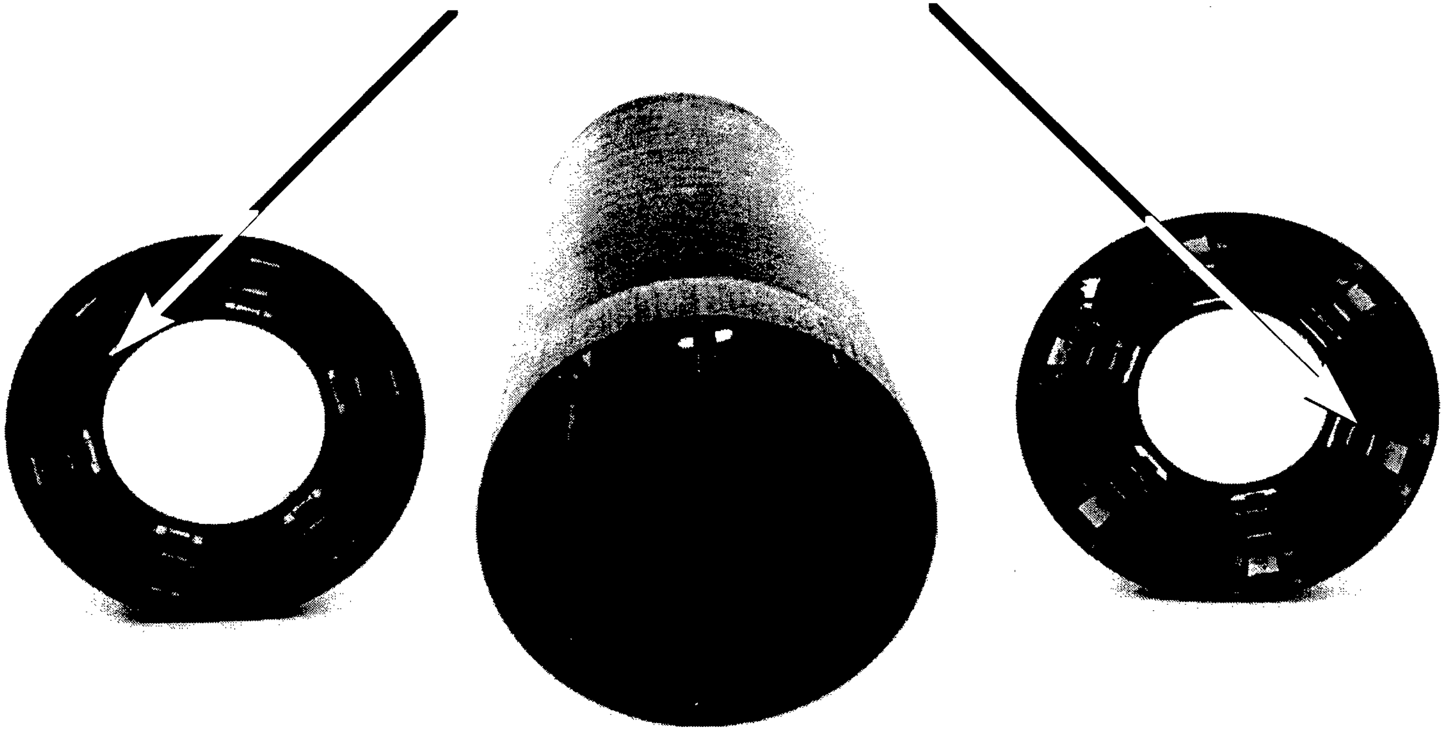






R&D Thermoplastic Tailboom Program

Doublers to strengthen frame cut-outs



AVIATION APPLIED TECHNOLOGY DIRECTORATE

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R&D Thermoplastic Tailboom Program

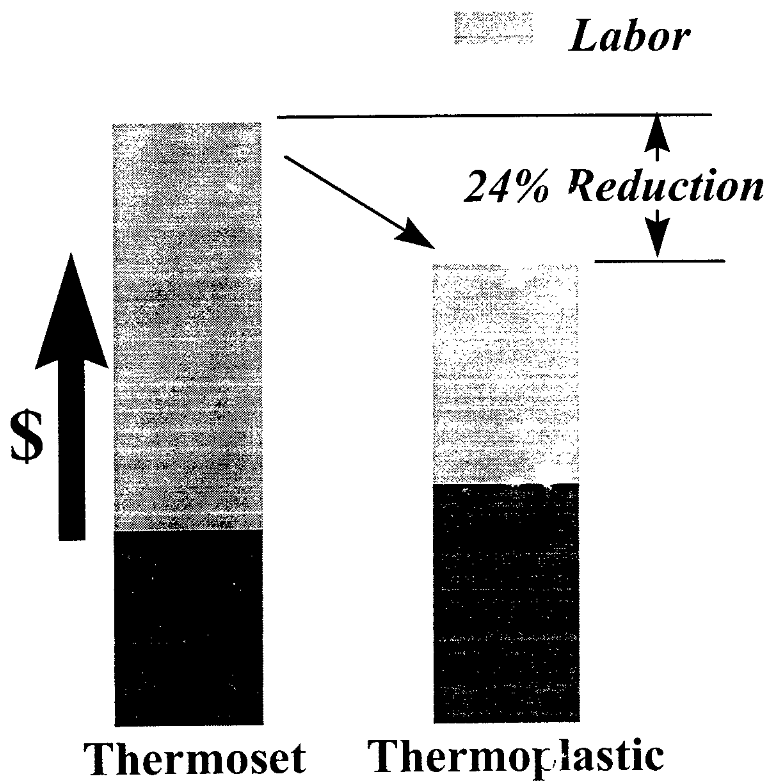
- **LONGERONS**
  - √ Single Tool - Two tools would reduce cost to 6 Mhs/Pound
  - √ High percentage of time in pressure vessel
  - √ 30% reduction with IR heaters
- **FRAMES**
  - √ Most Expensive Part to Make
    - Stamping channel preforms
    - Co-consolidation
  - √ C - Channel was fabricated in four 90° sections
    - Hand lay-up then cut to a circular arc
    - Polyimide sheets placed in center of laminate
  - √ Full C -Channel frame could be fabricated in one step
- **SKIN**
  - √ Increasing size of tape would speed up winding
    - Increase tape thickness {reduces # of plies}
    - Increase tape width {reduces # of strips per ply}

Fabrication Cost Summary

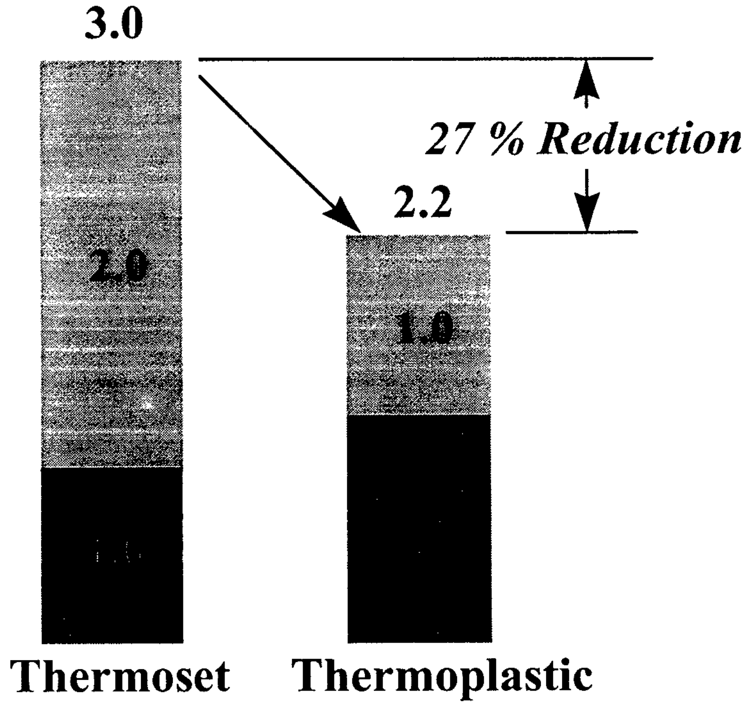
Component	Completed Part MH/Lb	Completed Part MH	Possible Reduction MH/Lb	Possible Reduction MH	% Reduction
Longeron	7.5	126.0	6.0	100.8	
Frame	25.0	132.5	12.0	63.6	
Skin	2.5	43.0	2.0	34.4	
Adjusted	7.8		5.1		34.6
Total		301.5		198.8	34.1

R&D Thermoplastic Tailboom Program

Thermoset vs Thermoplastic Panels



Source of Data: January 1995
Journal of Advanced Materials



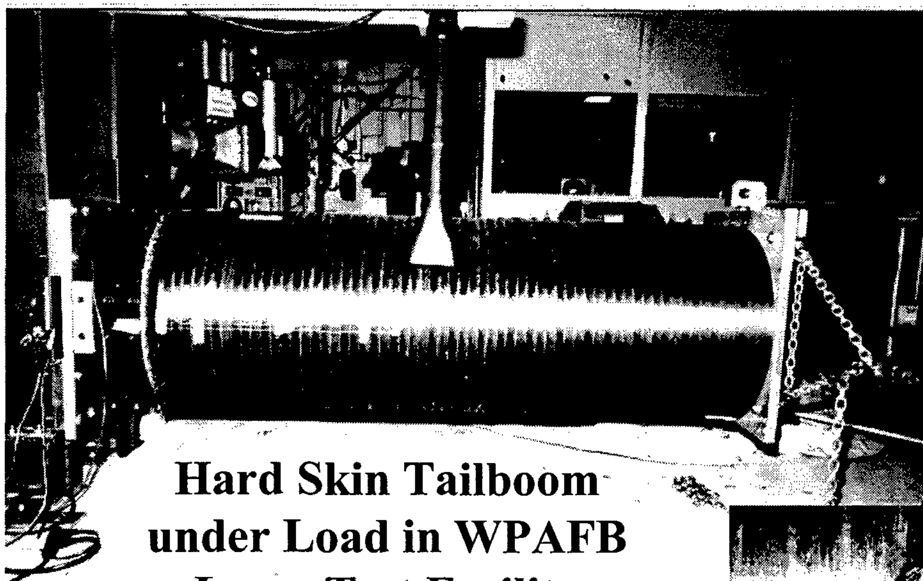
Source of Data: Aviation Applied
Technology Directorate {AATD}

R&D Thermoplastic Tailboom Program

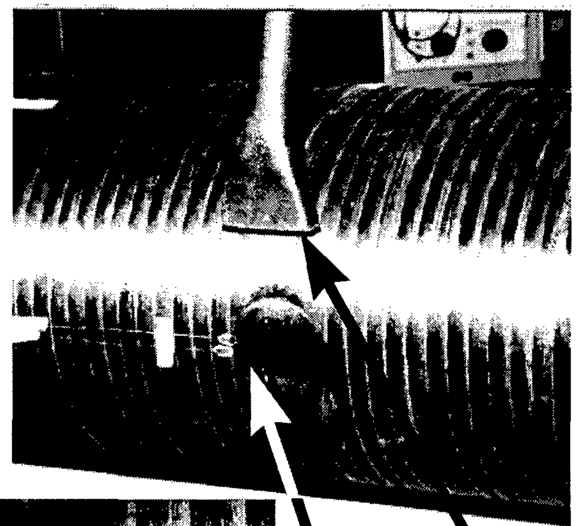
Test Matrix

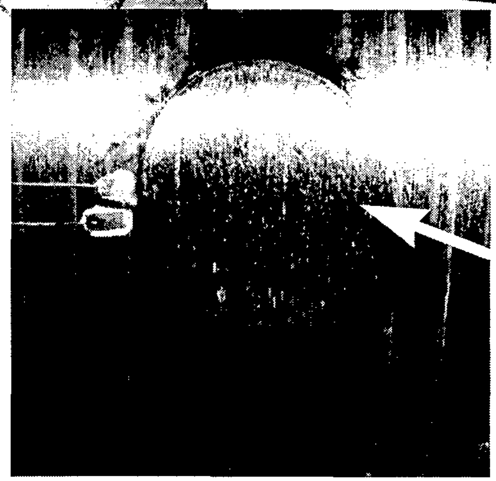
Specimen	Baseline Stiffness	Ballistic	Ballistic Fatigue	Laser & Repair	Patch Fatigue	Ultimate
16 -Ply IM7/PEEK {Military Grade}	X	X	X			X
16 -Ply AS4/PPS { Commercial}	X	X	X			X
10 -Ply IM7/PEEK {Military Grade}	X	X	X			X
16 -Ply IM7/PEEK {Military Grade}	X			X	X	
10 -Ply IM7/PEEK {Military Grade}	X			X	X	

R&D Thermoplastic Tailboom Program



Hard Skin Tailboom under Load in WPAFB Laser Test Facility

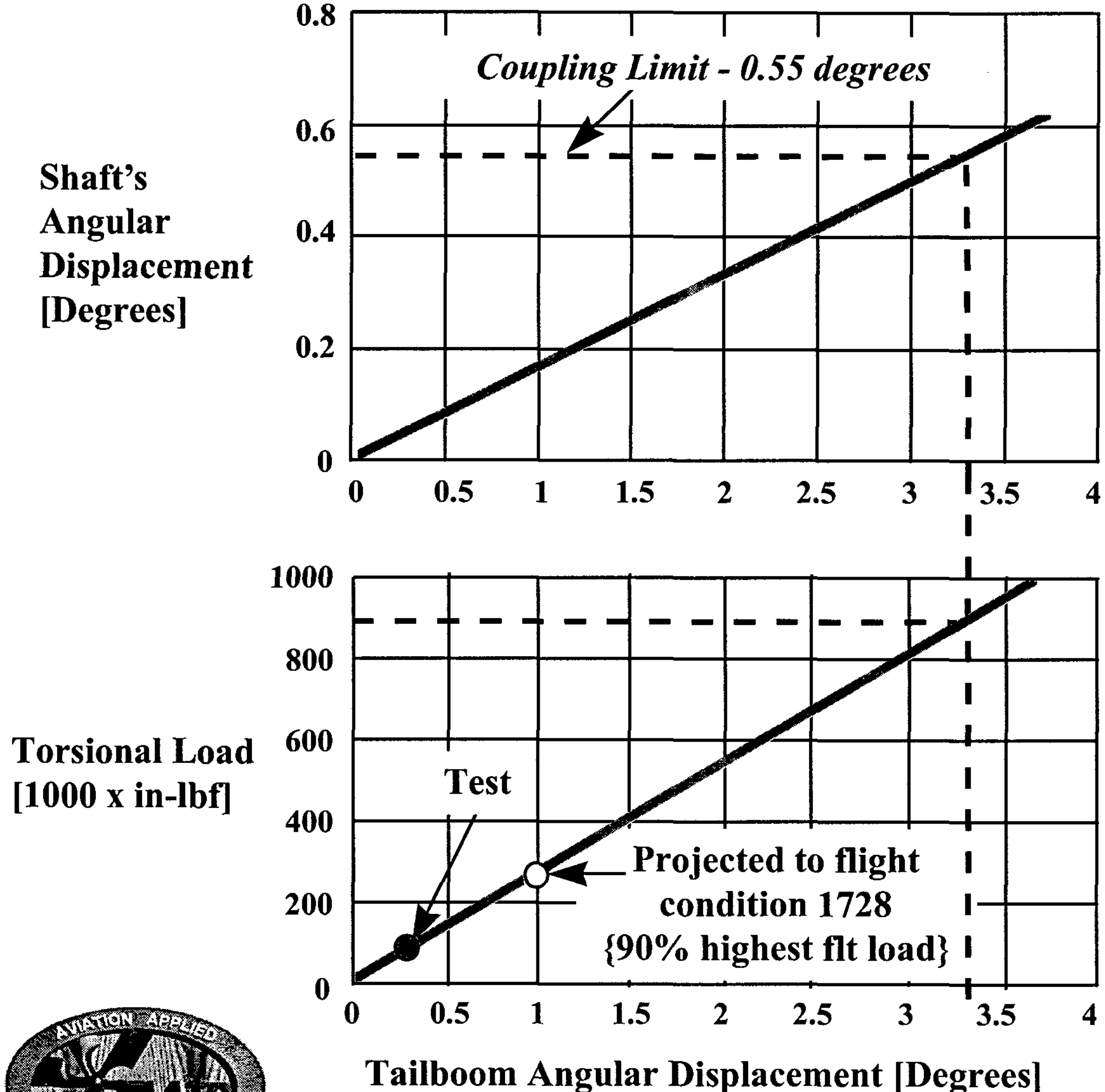




NOTE:

- Temperature on surface reached 1300°C{~2400°F}
- Damage - less than anticipated
- Power setting - significantly higher than typical threat levels

R&D Thermoplastic Tailboom Program



NOTES:

- Coupling misalignment limit of 0.55 degrees is produced by 3.3degrees of tailboom displacement
- Tailboom displacement requires 890,000 in-lbf torsional load

Conclusion:

Damaged tailboom maintains the tail rotor shaft's misalignment within allowable limits

R&D Thermoplastic Tailboom Program

Conclusions

- **20% estimated weight savings over thermosets**
- **25% estimated fabrication cost savings over thermosets**
- **No autoclave was required**
- **No fasteners were used between frames, longerons, & skins**
- **Limited delamination due to 23mm HEI damage**
- **Laser test level significantly higher than typical threat levels**
- **Field repair successfully demonstrated**
- **Met strength & stiffness requirements after 23mm HEI damage**
- **High temperature environment operation {IM7/PEEK, 250° F wet, 290° F dry}**
- **Excellent toughness**
- **Thermoplastics is NOT high risk technology any longer**

Enhancing AIRCRAFT SURVIVABILITY
a Vulnerability Perspective

COMPOSITE STRUCTURE DESIGNS:
LESS VULNERABLE, MORE AFFORDABLE

Bill Baron
Air Force Research Laboratory
Jamie Childress
Boeing Defense and Space
October 23 1997

Design for Affordability

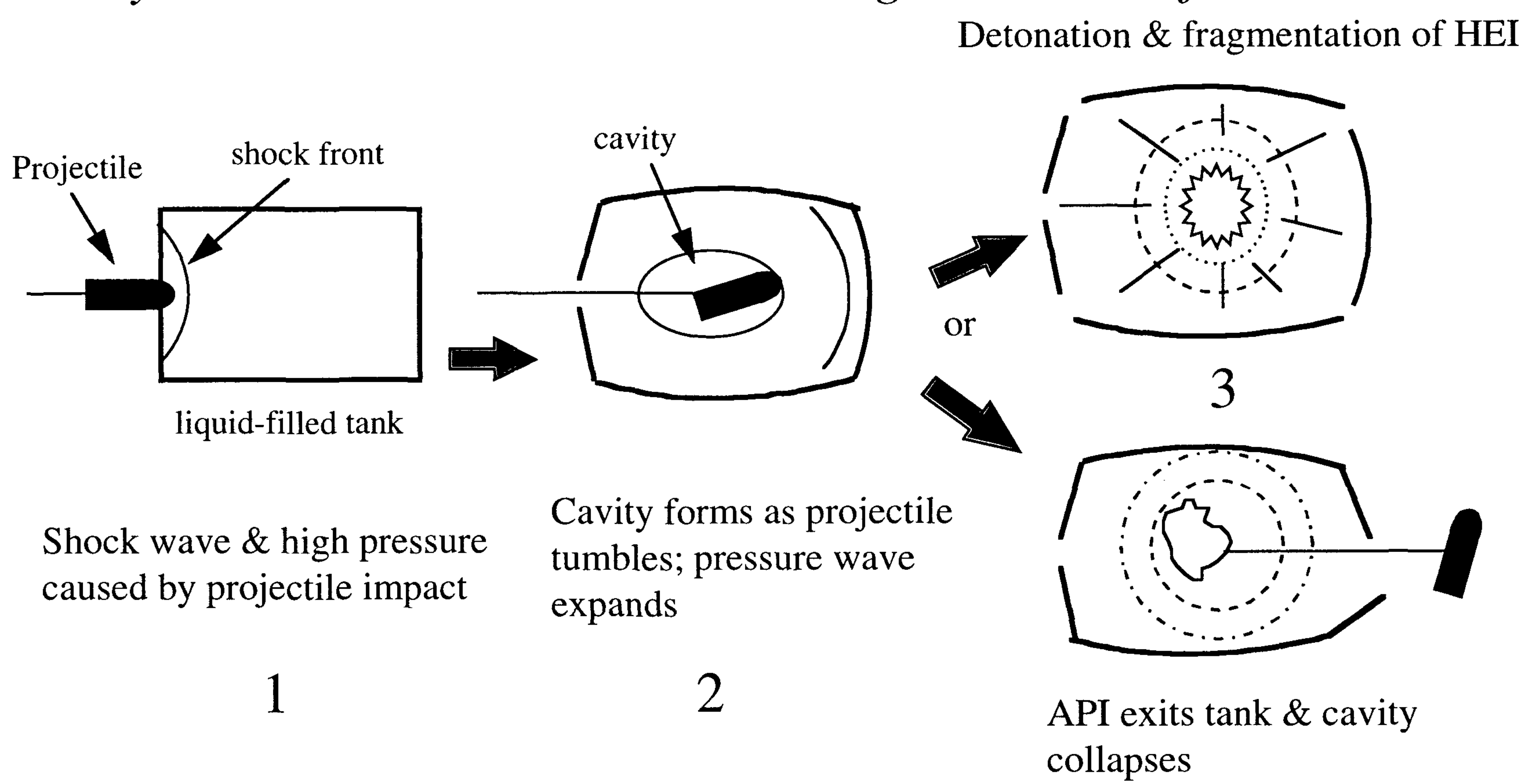
AFFORDABILITY = $f\{\text{LOW COST} + \text{PERFORMANCE}\}$

- Survivability is a key component of performance

- Aircraft Lethality is improved through the development of survivable structure
- Structure is damaged in almost all ballistic events
- Vulnerability must be considered upfront in an aircraft development program
  - Design space is fixed early; limiting future solutions if the design does not meet the Live Fire Law requirements
  - Retrofit of primary structure is not an affordable option
  - Vulnerability reduction features can be exploited efficiently

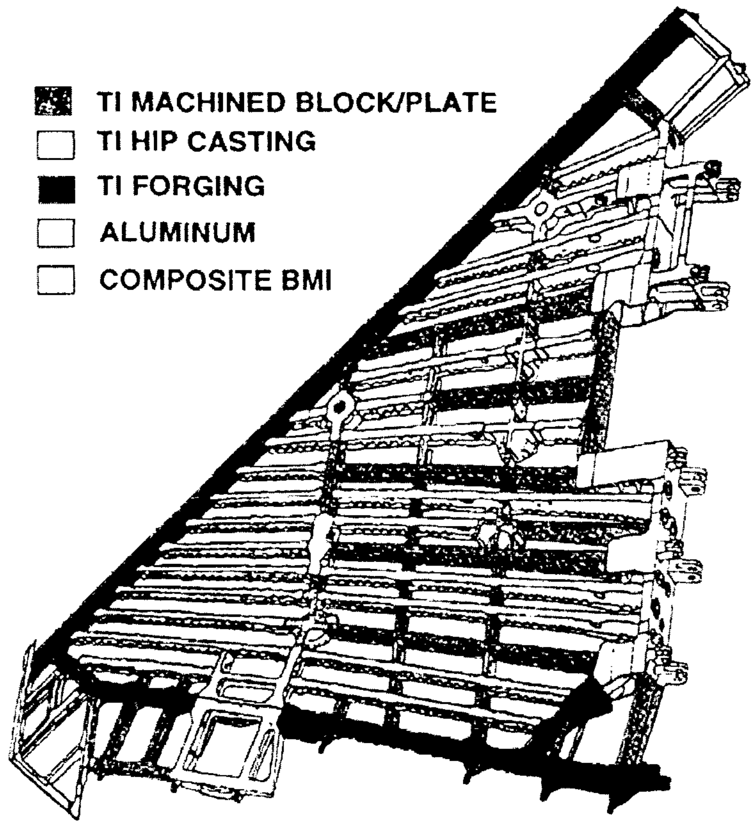
Hydraulic Ram Threat

Hydraulic Ram is the critical design condition for structure



Recent Experience

- Titanium spars in F-22 wing required to meet Live Fire requirements
- F-22 Wing Box Total Weight = 3130 lbs per Ship Set
- Increased Weight of Titanium Spars, Additional Fasteners, and Ribs = 120 lbs per Ship Set
- 120/3130 = 4% Weight Increase Due to Hydrodynamic Ram



Increased cost and weight of the survivable structural system

Survivable Composite Structure
Myth or Reality?

Current Design Practice

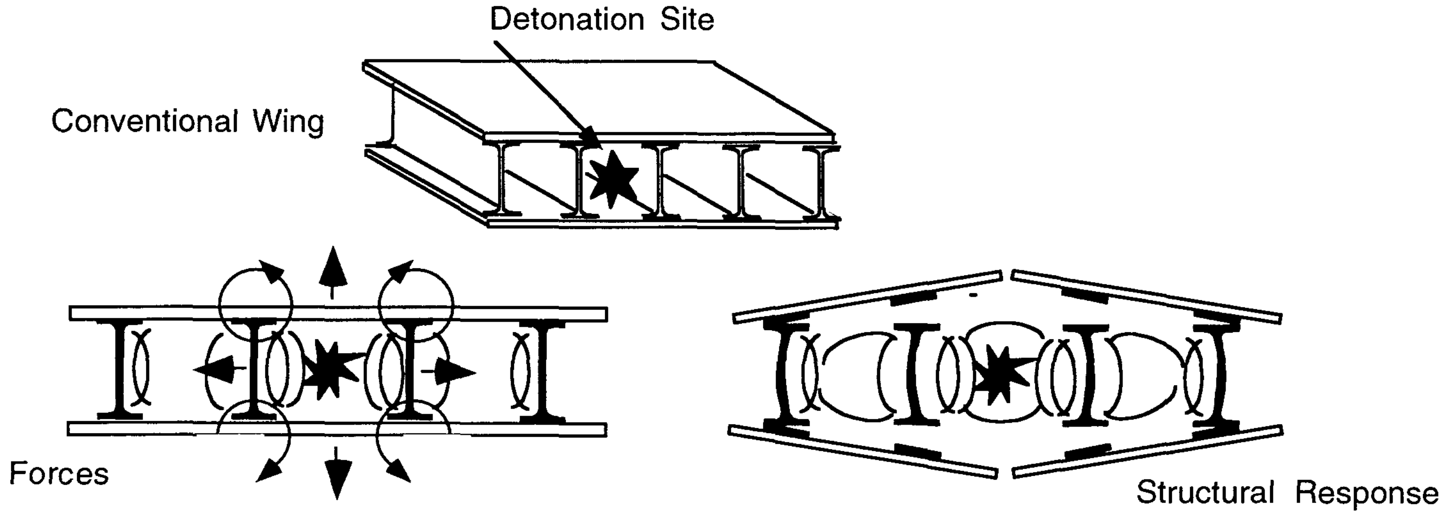
- Apply metallic design approach
- Mechanical fasteners to provide containment
- Use toughened material matrix
- Use parasitic materials to disrupt coupling

COMPOSTIES PERCEIVED TO BE LESS SURVIVABLE

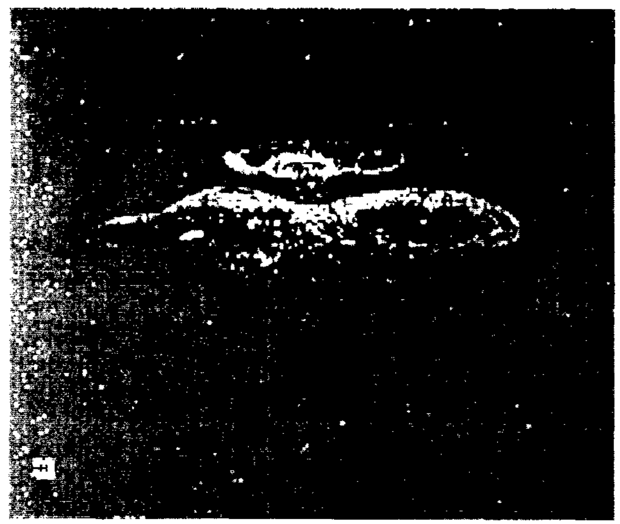
Design for Affordable Composite Structure

- Tailor fiber architecture in unitized designs for robust joints
- React hydraulic ram pressures in the composite fibers
- Establish zones of controlled failure through stiffness tailoring
- Design to establish a pressure impedance mis-match

Conventional Failure Modes

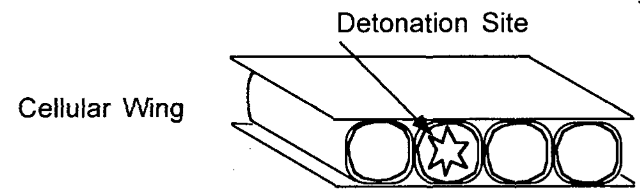


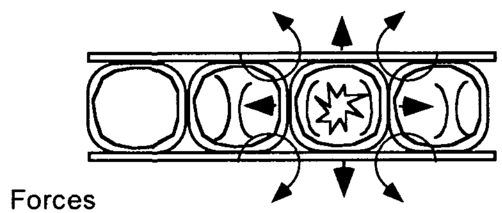
- Joints are the "achilles heel" of the structural system
- Bolt pull-through allows panel separation
- Pressures fully coupled between bays

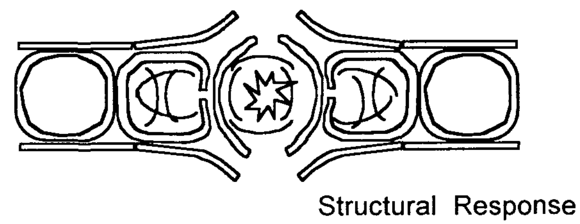


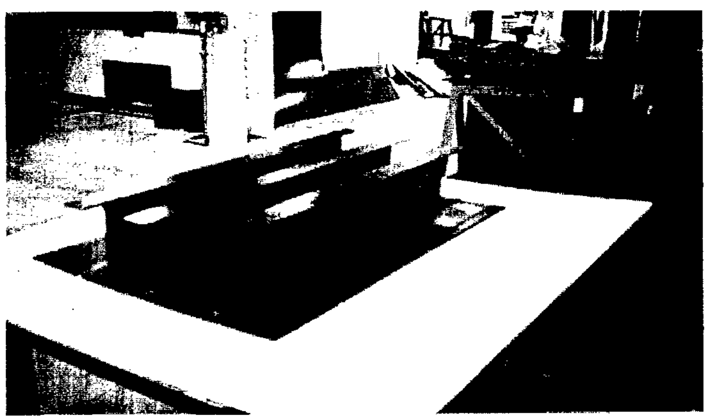
23mm API; Bolted Composite Panel C-Scan

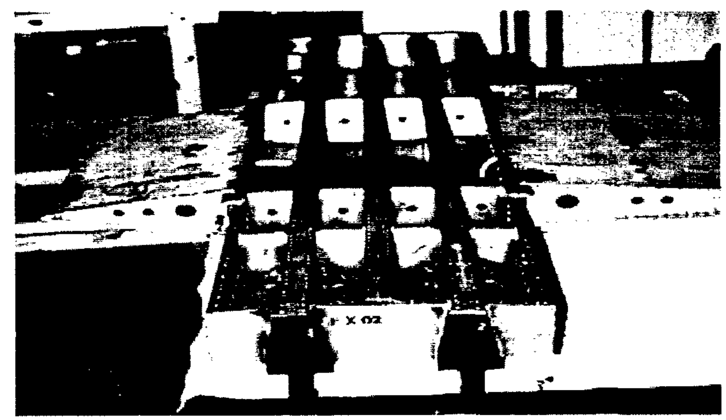
Unitized Composite Design







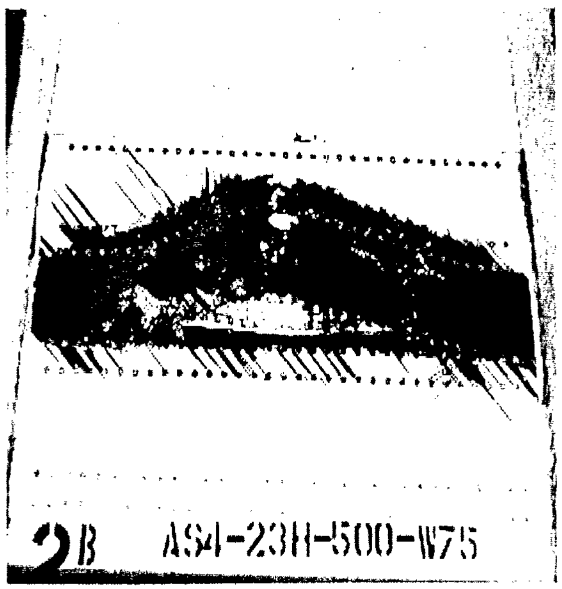




- Web plies wrap around the cell to form the inner moldline
- Testing conducted under fully simulated combat conditions
  - Structural bending load, 23 HEI, Hydraulic Ram & Airflow

Results of Testing
23mm HEI

LOWER COST & LOWER WEIGHT ALL COMPOSITE DESIGN DEMONSTRATED IMPROVEMENT IN SURVIVABILITY

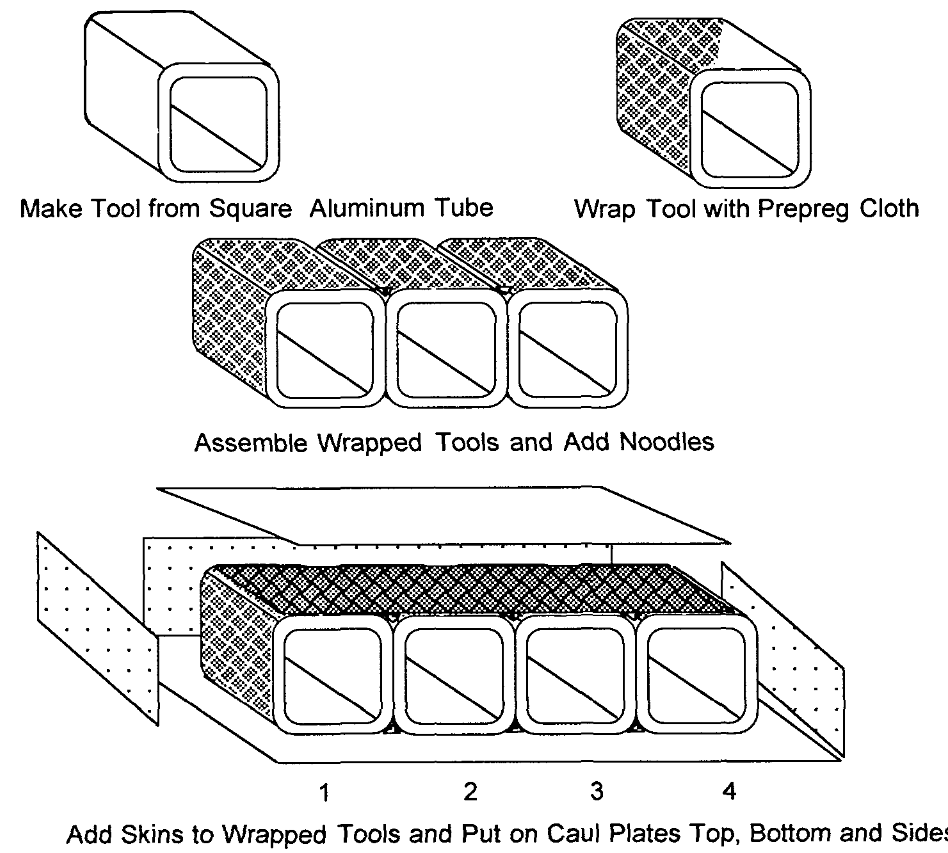


- CONVENTIONAL BASELINE STRUCTURE
- METALLIC SUBSTRUCTURE & COMPOSITE SKIN
- EXTENSIVE MULTIBAY DAMAGE

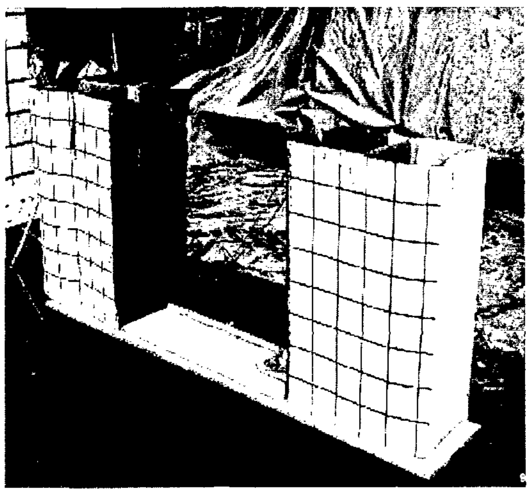
- COCURED COMPOSITE DESIGN
- CELLULAR DESIGN CONFIGURATION
- ZPINNED-FASTENERLESS LOWER SKIN
- CONTROLLED MEMBRANE TENSION FAILURE MODE

CONCEPT SCALE-UP

- Wrap Composite Fabric Around Cell Tooling
- Assemble Cells
- Apply Skin to Assembly
- Z-Pin "Spars" to Skin (Along Cell Joint Line)
- Ultrasonic Z-Pinning Approximately 5-10X Faster Than Bolting
- Cure Entire Assembly



RESULTS OF TESTING



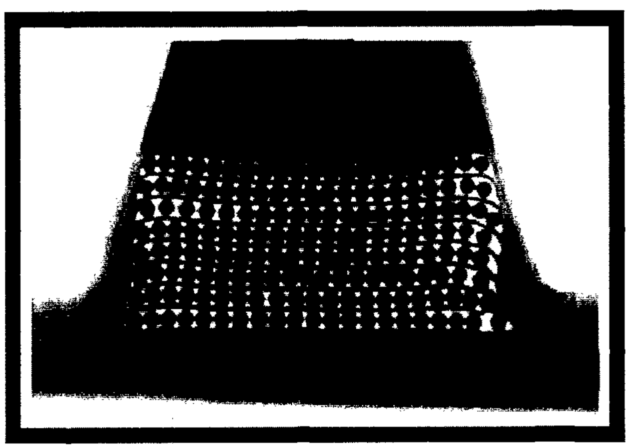
Cellular Box

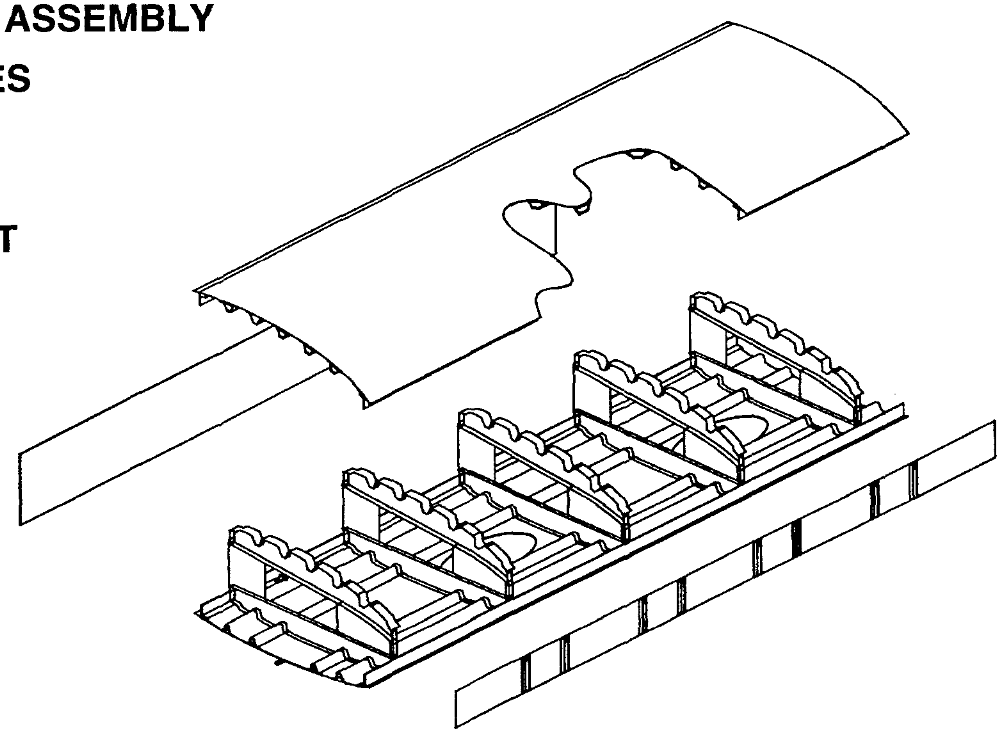
- Muliple tests conducted with 30mm HEI Threat
- Tests conducted with Box Full of Water and with 60%-full decoupled
- Demonstrated Controlled Damage to the impacted and adjacent bays

- Damage dominated by skin failure
- Pressure transmitted through adjacent bays can be significantly reduced through decoupling
- Decoupling allows reflected fluid momentum to vent

DESIGN FOR DEEP-SECTION WING STRUCTURE

- WINGBOX DESIGNEDTO ALLOW SIMPLIFIED ASSEMBLY
- COMPONENT FABRICATION DEMONSTRATES INNOVATIVE LOW COST PROCESSES
  - 50% COST REDUCTION
  - STRONGER, MORE DAMAGE TOLERANT
  - SAME WEIGHT





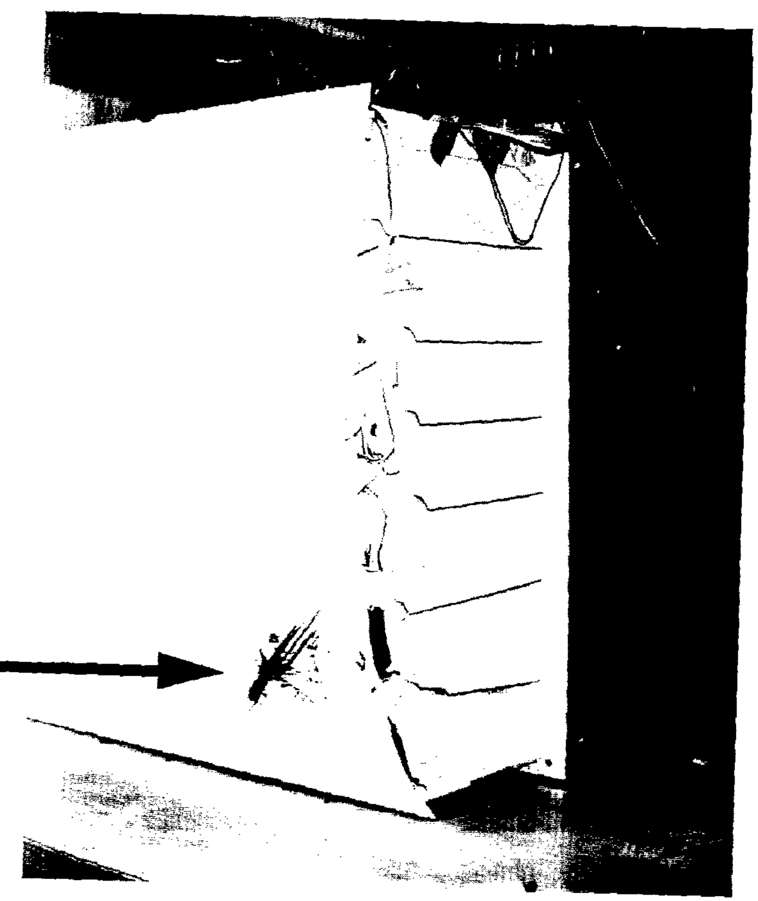
- TAPE LAYED SKINS WITHINTEGRAL PULTRUDED - ROD REINFORCED HAT STIFFENERS
- ENABLE IMPROVED LOAD PATH MANAGEMENT

INTERLOCKED BONDED RIBS REACT PULLOFF LOADS IN SHEAR

DEEP SECTION TEST RESULTS

- BONDED CONSTRUCTION *IS* *SURVIVABLE*
- FASTENER REDUCTION REDUCES COST *DOES NOT* INCREASE VULNERABILITY
- COMBINATION OF PULTRUDED RODS AND SOFT SKINS CONTAINS DAMAGE - LOAD PATHS LARGELY MAINTAINED

FIVE STIFFENER - TWO RIB TEST PANEL RESULTS



23 mm API EXIT DAMAGE

SIMULATED FUEL

HIT ON ROD REINFORCED STIFFENER

LESSONS LEARNED
Keys to Affordable Composite Structure

- Elastic joint behavior, avoid stiff joints like sinewave spars
- Strong joint/weak skin
- Wide spar caps
- Fibers wrap continuous around fuel bay
- Z-Pinned substructure/skin attachment prevents peel
- Provide weak point in skin at desired failure location
- Interlocked bonded structure
- Design structural layout with fuel management for hydraulic ram protection in mind
- Manage loads around damage zones

SURVIVABLE UNITIZED DESIGN COST SAVINGS POTENTIAL

- Designing for Survivability can offer significant cost savings
  - F-22 Wing Set Weight Delta Due to Hydram = +120 lbs 120 lbs x $1000/lb Lifecycle Cost = $120,000
  - F-22 Wing Set Cost Delta Due to Hydram = $220,000
  - Cell Design Eliminates 8,000 Wing Fasteners; 8,000 x $50/ Fastener = $400,000

- Total Savings $120K + $220K + $400K = $740K/Aircraft
- Production of 3000 aircraft; 3000 x740K = $2.22 Billion

CONCLUSIONS

- Conventional designs are not more affordable than "all-composite" design approaches
- Survivability must be traded upfront as a structural requirement in the conceptual/preliminary design stage of development (knowledge gained through early "build & bust")
- Composites provide the designer with strength/stiffness management freedom to control failure characteristics
- Designs must be demonstrated to accommodate multidisciplinary requirements
  - Emerging structural design concepts (e.g. stitching, zpinning, interlocked bonding, textiles)
  - Advanced manufacturing(e.g. ebeam, RTM, material placement)
  - Subsystems integration

BOEING

Aircraft Accidents / Incidents: Extending the Vulnerability Database

ADPA / NSIA Enhancing Aircraft Survivability

A Vulnerability Perspective

Michael Meyers

The Boeing Company
McDonnell Aircraft and Missile Systems
21-23 October 1997

GP72985001.cvs

BOEING

Vulnerability Program Elements

- Aircraft Configuration Requirements
- FMECA
- Flight/Mission Essential Functions
- Damage Modes and Effects Analysis
- Vulnerability Assessment and Hardening
- Trade-Off Studies
- Inputs to Survivability Assessments
- Live Fire Testing
- Feedback to Integrated Product Definition

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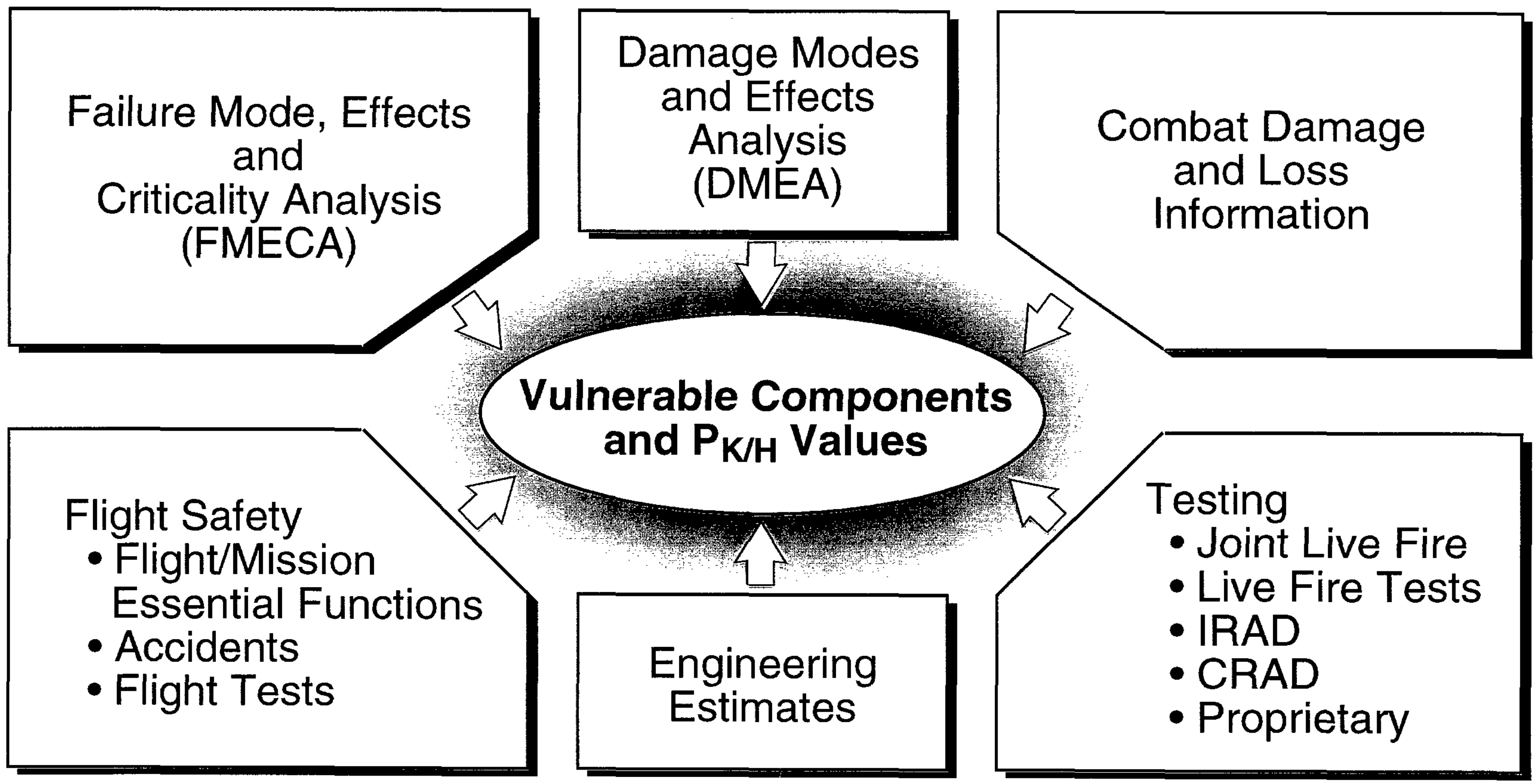
Vulnerable Component Determination



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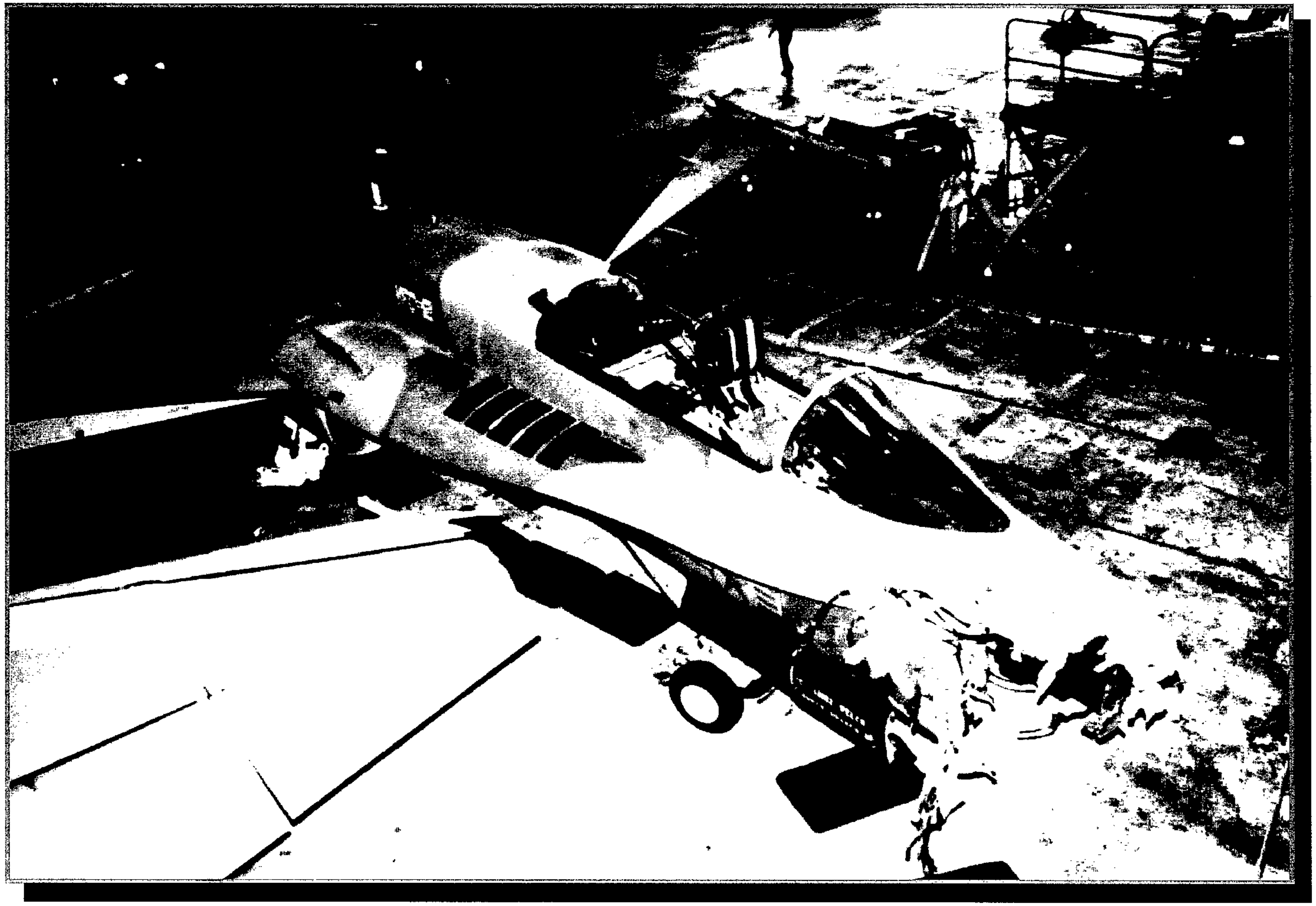
Forward Fuselage Damage

GP72985006.cvs

650

Forward Fuselage Damage



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Wing and Vertical Tail Damage

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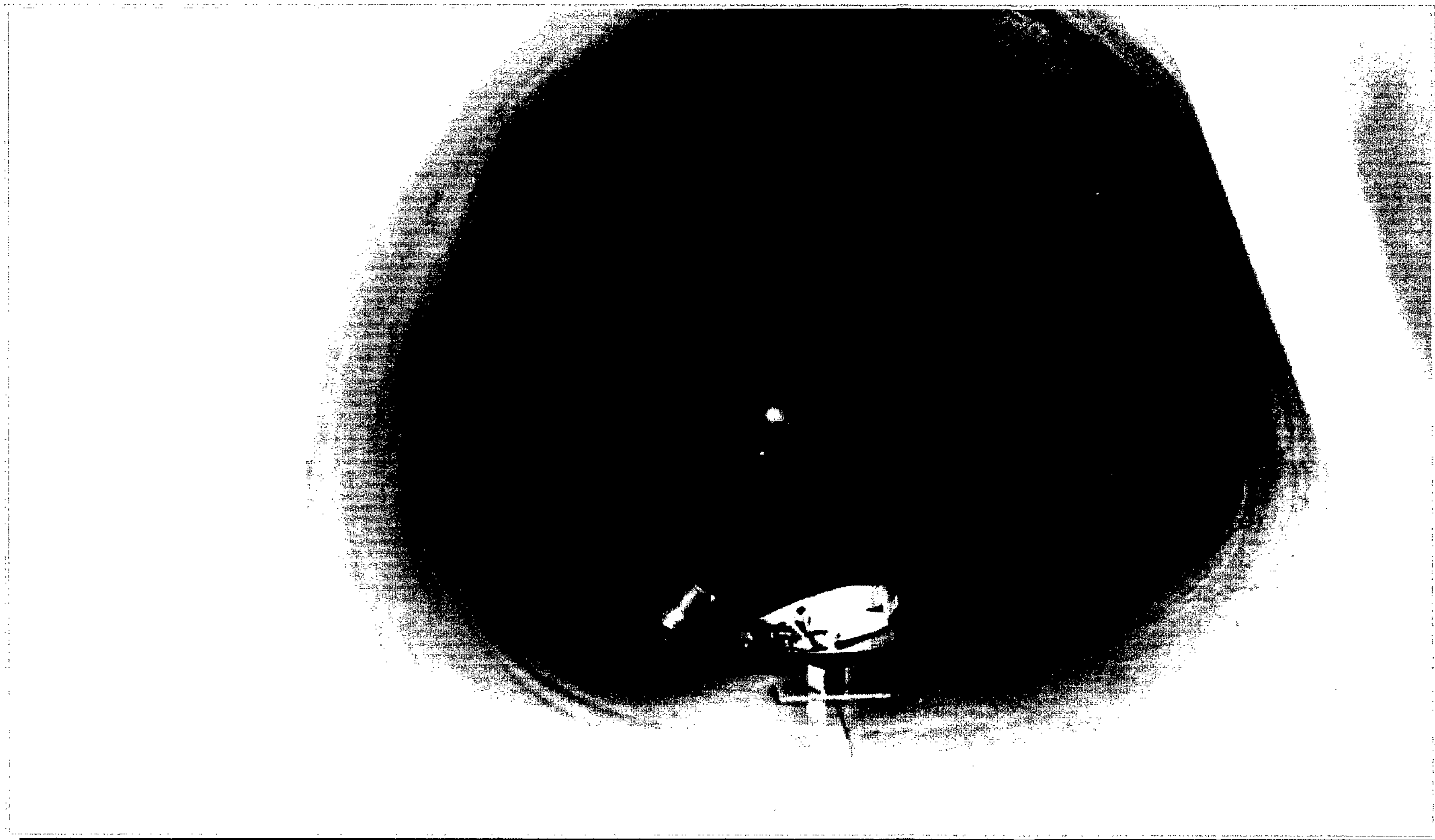
Engine FOD



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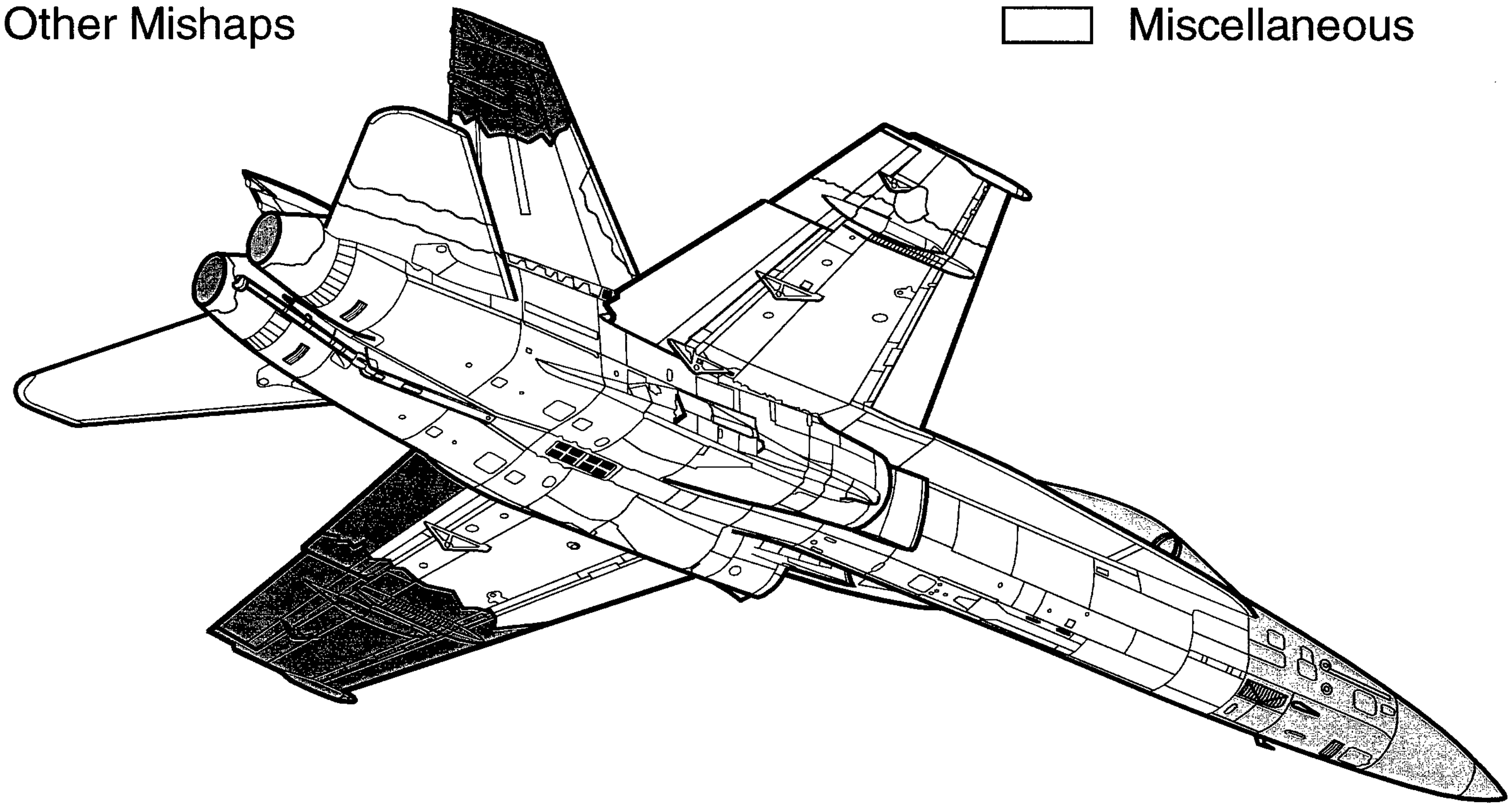
In-Flight Lost Surface Areas on Recovered F/A-18s

- Mid-Air
- Other Mishaps

April 23, 1996 Mid-Air

Miscellaneous



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Summary

- Mid-Air Accidents Are Infrequent
- Damage Tolerant Structure and Subsystems Increase the Chances of Surviving Mid-Air Accidents
- Utilization of Operational Accident Data Is Part of the Vulnerability and System Safety Programs for All F/A-18 Aircraft
- The Results Are Not Necessarily Transferable to Non-F/A-18 Aircraft

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REDUCING CHEMICAL, BIOLOGICAL AND RADIOLOGICAL VULNERABILITY THROUGH DESIGN

Jerry Burblis
Sikorsky Aircraft Corporation
Ph: (203) 386-6092
Fx: (203) 386-5925
e-mail: gburblis@sikorsky.com

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

CBR, NBC, B/C, WHAT IS IT?

THREAT CHARACTERISTICS:

CHEMICAL AGENTS - TYPES, DISSEMINATION METHODS, DURATION
THREAT TO AIR VEHICLE CREW OR EQUIPMENT?

BIOLOGICAL AGENTS - TYPES, DISSEMINATION METHODS, DURATION
THREAT TO AIR VEHICLE CREW OR EQUIPMENT?

NUCLEAR - THREAT TO AIR VEHICLE OR CREW?

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

CBR SURVIVABILITY REQUIREMENTS:

- RELATIVELY NEW

- NOT MANDATED FOR PREVIOUS SIKORSKY AIR VEHICLES

- RAH-66 COMANCHE IS THE FIRST HELICOPTER DEVELOPED WITH CBR REQUIREMENTS SPECIFIED IN THE PERFORMANCE WEAPON SYSTEM SPECIFICATION

- RAH-66 REQUIREMENTS FOCUSED ON:

  MATERIAL RESISTANCE TO CBR CONTAMINANTS AND DECONTAMINANTS

  COCKPIT/AVIONICS PROTECTION

  DECONTAMINATION

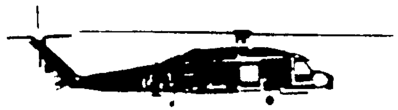
  DETECTION

UNITED TECHNOLOGIES
SIKORSKY AIRCRAFT

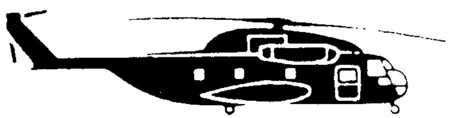
REDUCING CBR VULNERABILITY THROUGH DESIGN

CBR RESISTANCE NOT A DESIGN REQUIREMENT

UH-60A
UH-60L
MH-60K



HH-60K
SH-60B
SH-60F
HH-60J



HH-53B
HH-53C
CH-53C
HH-53H
MH-53J

CH-53E
MH-53E

CBR HARDEN DESIGN BASED ON PWSS REQUIREMENTS

RAH-66

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

RAH-66 COMANCHE NBC SURVIVABILITY FEATURE OVERVIEW

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

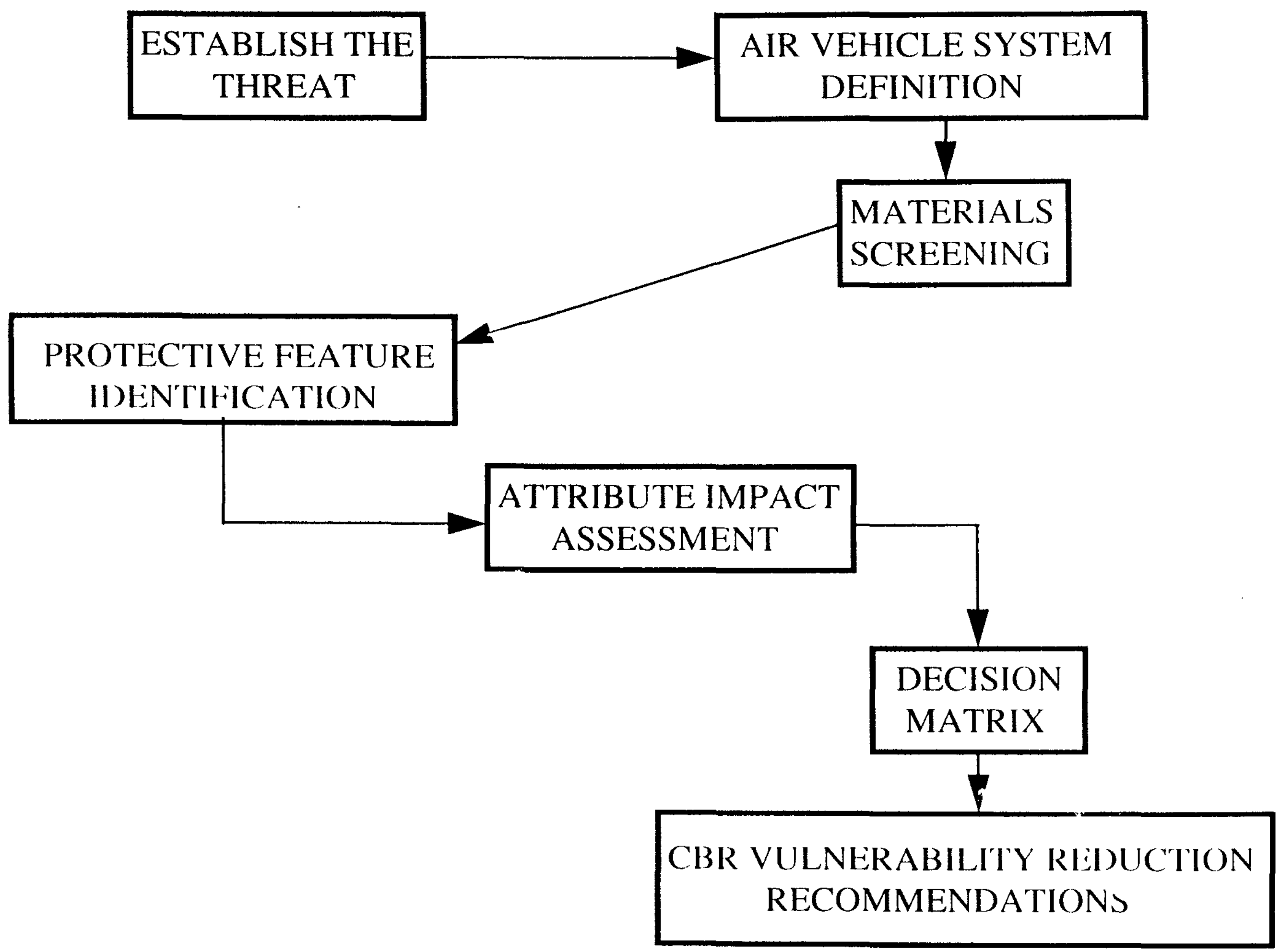
OBJECTIVE:

IMPROVE AIR VEHICLE SURVIVABILITY THROUGH THE INCORPORATION OF DESIGN FEATURES WHICH WILL ENHANCE THE SYSTEM'S ABILITY TO EFFECTIVELY CONDUCT OPERATIONS IN A CBR CONTAMINATED ENVIRONMENT

UNITED TECHNOLOGIES
SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

APPROACH TO CONDUCTING A SYSTEM CBR VULNERABILITY ASSESSMENT:



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REDUCING CBR VULNERABILITY THROUGH DESIGN

AIR VEHICLE SYSTEM DEFINITION:

ACQUIRE DETAILED INFORMATION ON ALL VEHICLE SYSTEMS, SUBSYSTEMS, AND COMPONENTS, INCLUDING AN UNDERSTANDING OF HOW EACH OPERATES

DETERMINE CRITICALITY - FLIGHT CRITICAL
MISSION CRITICAL
NOT FLIGHT OR MISSION CRITICAL

DETERMINE LOCATION OF SYSTEM, SUBSYSTEM, OR COMPONENT ON OR WITHIN THE AIR VEHICLE

REGIONALIZE THE AIR VEHICLE TO FACILITATE ASSESSMENT

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REDUCING CBR VULNERABILITY THROUGH DESIGN

MATERIALS SCREENING:

SCREEN ALL MATERIALS FOR CBR CONTAMINATION AND DECONTAMINATION RESISTANCE

UTILIZE EXISTING PARTS LISTS TO DETERMINE MATERIAL TYPES USED FOR ALL SYSTEMS AND COMPONENTS BEING ASSESSED

CATEGORIZE AS SUSCEPTIBLE TO CBR DAMAGE OR NON-SUSCEPTIBLE DUE TO INHERENT MATERIAL QUALITIES

DETERMINE LEVEL OF POTENTIAL DEGRADATION - FULLY MISSION CAPABLE, PARTLY MISSION CAPABLE, NOT MISSION CAPABLE

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REDUCING CBR VULNERABILITY THROUGH DESIGN

PROTECTIVE FEATURE IDENTIFICATION:

ESTABLISH RECOMMENDATION MATRIX FOR PROVIDING ENHANCED PROTECTION FEATURES AND ALTERNATIVES BASED ON:

- LOCATION - SYNERGISTIC PROTECTION PROVIDED
- CAN THREAT PHYSICALLY CONTACT PART UNDER NORMAL OPERATING CONDITIONS?
- MATERIAL CHANGE
- PROTECTIVE COATING
- RELOCATE AND PROVIDE ENVELOPE PROTECTION
- ENHANCE DETECTION CAPABILITIES TO REDUCE VULNERABILITY THROUGH AVOIDANCE

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REDUCING CBR VULNERABILITY THROUGH DESIGN

PROTECTIVE FEATURE IDENTIFICATION:(CONT.)

- IDENTIFY SUSCEPTIBLE MATERIALS WHICH CANNOT BE PROTECTED AND ALERT CUSTOMER TO FOLLOWING POSSIBILITIES:
  - DEGRADATION WILL OCCUR FOLLOWING EXPOSURE
  - REPLACEMENT MANDATED AFTER EACH OCCURRENCE
  - CANNOT BE DECONTAMINATED
  - ADDED LOGISTICAL BURDEN
- ENSURE PRIMARY DESIGN FUNCTION OF THE SYSTEM OR COMPONENT IS NOT ADVERSELY AFFECTED BY THE INCORPORATION OF ANY CBR PROTECTIVE FEATURE

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REDUCING CBR VULNERABILITY THROUGH DESIGN

ATTRIBUTE IMPACT ASSESSMENT:

ESTABLISH A RELATIVE IMPACT ASSESSMENT MATRIX WITH RESPECT TO KEY ATTRIBUTES SUCH AS:

- POWER REQ'TS
- WEIGHT
- VOLUME
- LOGISTICS EFFECTS
- MAINTENANCE EFFECT
- MISSION EFFECTIVENESS
- CHEMICAL RESISTANCE IMPROVEMENT OVER BASELINE
- BALLISTIC TOLERANCE
- COOLING REQ'TS
- COST
- MOPP IV COMPATIBILITY
- REPAIRABILITY EFFECT
- DECONTAMINATION EFFORT

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

DECISION MATRIX:

ASSESSMENT RESULTS ARE COMPILED INTO A PROTECTION FIGURE-OF-MERIT CHART

THIS CALCULATION PROCESS RELATES A PROTECTIVE DESIGN FEATURE TO THE NUMBER OF PARTS PROTECTED VS THE TOTAL NUMBER OF PART TYPES ASSESSED

THIS CHART ASSISTS IN DETERMINING WHICH FEATURES OFFER THE GREATEST POTENTIAL FOR CBR VULNERABILITY REDUCTION

UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

REDUCING CBR VULNERABILITY THROUGH DESIGN

RECOMMENDATIONS:

DEVELOP A CBR PROTECTIVE FEATURE "WISH" LIST FOR THE SPECIFIC SYSTEM

FOR AIR VEHICLES UNDER DEVELOPMENT THIS LISTING WOULD BE USED TO SUPPORT THE PRELIMINARY DESIGN PROCESS

ON MATURE AIR VEHICLE SYSTEMS THE LISTING WOULD BE UTILIZED TO SUPPORT A PHASED UPGRADE APPROACH CONSIDERING TIME AND FUNDING PROFILES

IN BOTH CASES THE LISTING WOULD SUPPORT TRADE-OFF STUDY EFFORTS AND MEASURE-OF-EFFECTIVENESS STUDIES

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REDUCING CBR VULNERABILITY THROUGH DESIGN

SUMMARY:

TAILOR THE CBR PROTECTIVE FEATURES TO PROVIDE AN OPTIMIZED LEVEL OF PROTECTION FOR THE SPECIFIC AIR VEHICLE DESIGN AND THE PRIMARY MISSION PROFILES IT IS DESIGNED TO CONDUCT

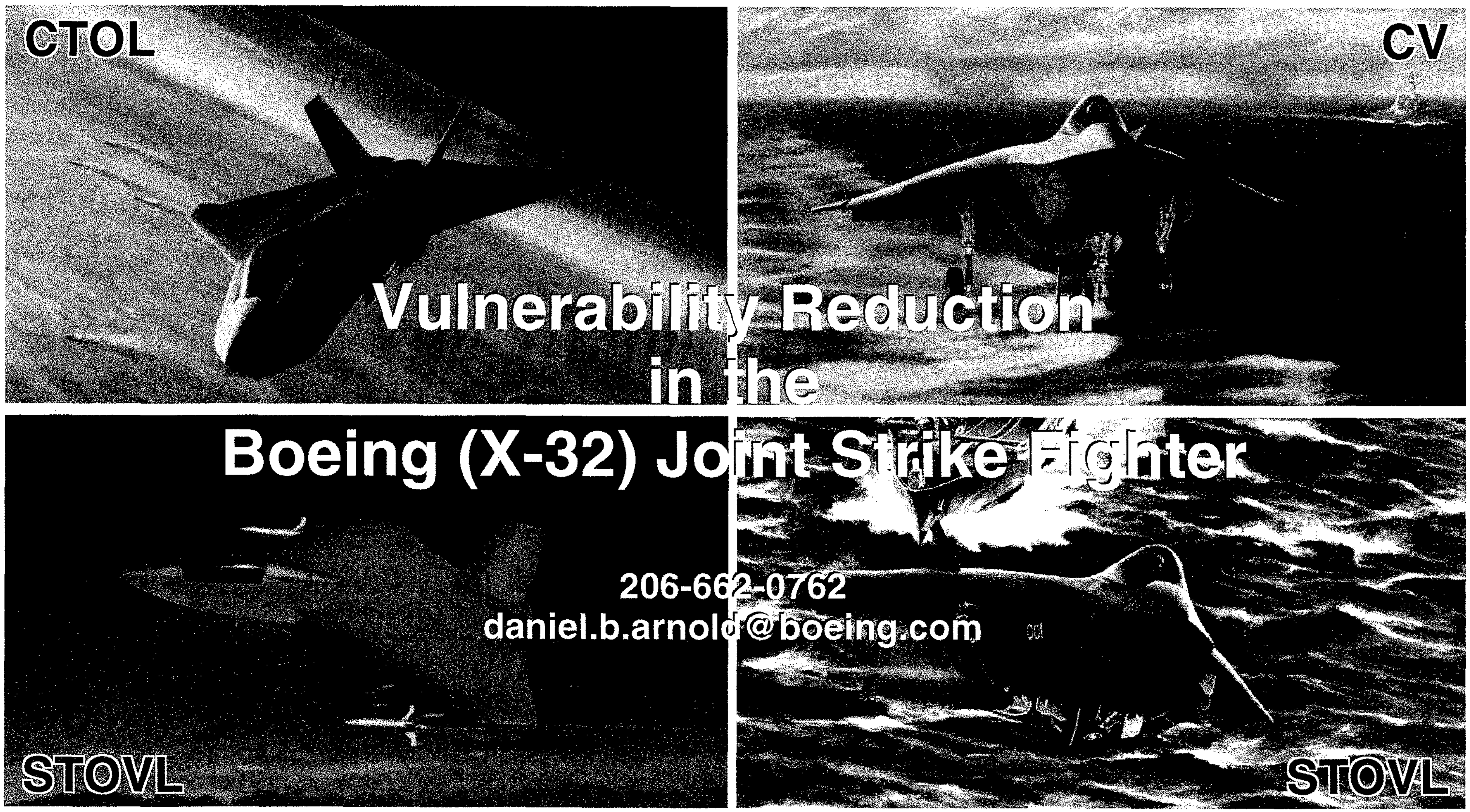
UNITED TECHNOLOGIES SIKORSKY AIRCRAFT

The following presentation is planned for the
ADPA/NSIA
Enhancing Aircraft Survivability
Conference
in
Monterey, CA
October 21-23, 1997

October 2, Draft

JOINT STRIKE FIGHTER JSF BOEING

Joint Strike Fighter Multi-Service Weapon System



Vulnerability Reduction in the Boeing (X-32) Joint Strike Fighter

206-662-0762
daniel.b.arnold@boeing.com

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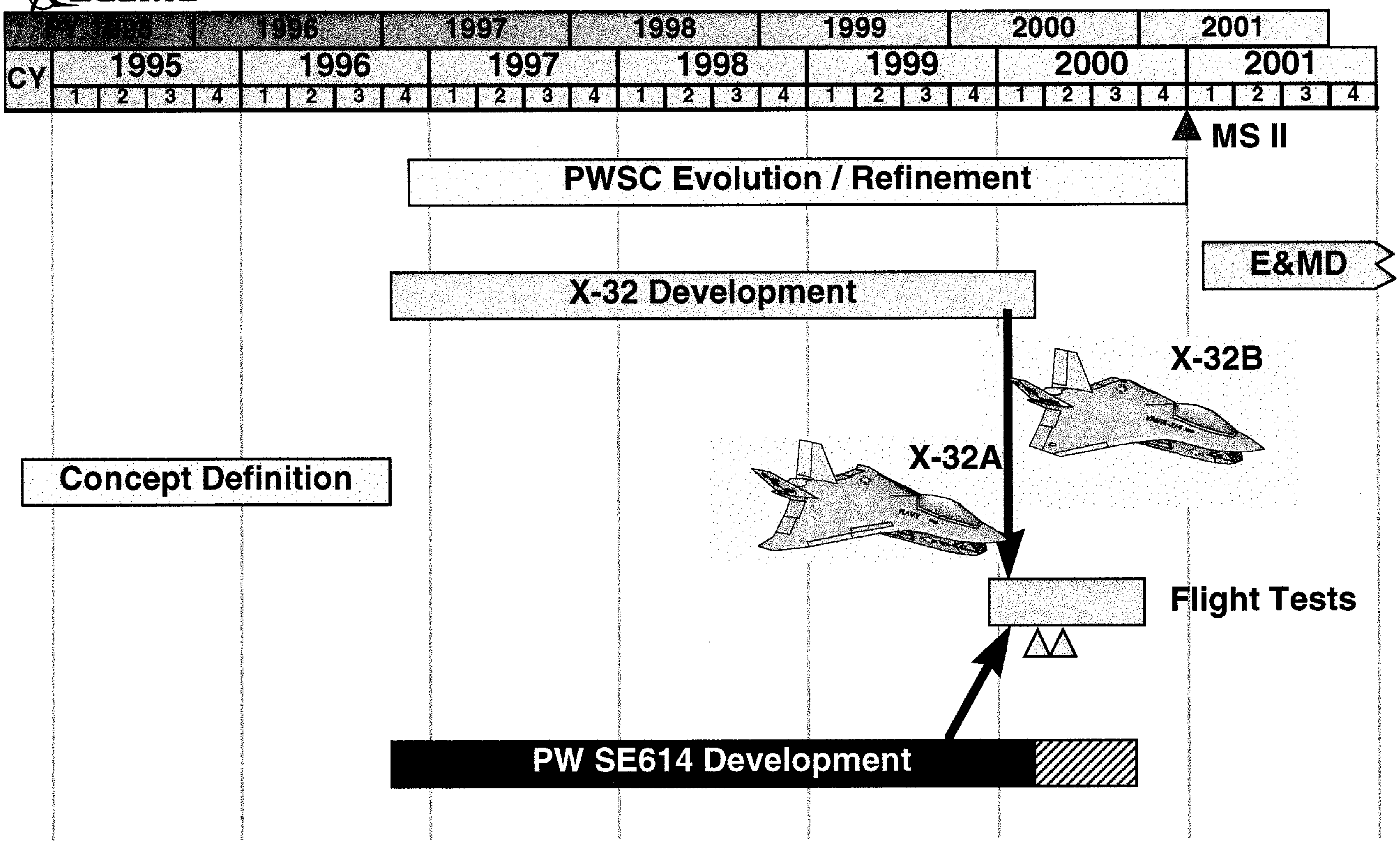
Concept Demonstration Program Schedule



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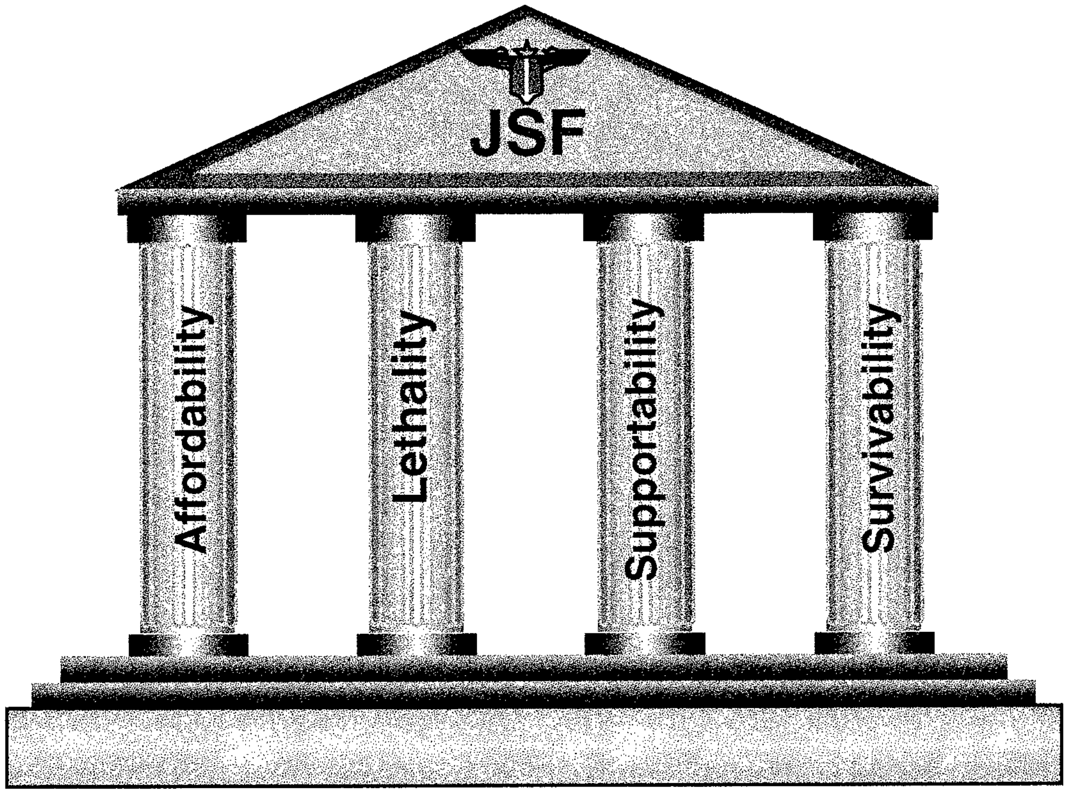
Requirements and Objectives

- Multi-Service Weapon System
  - Affordable
  - Operational Capability to Meet Warfighter Needs



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Multi-Service Design Concept

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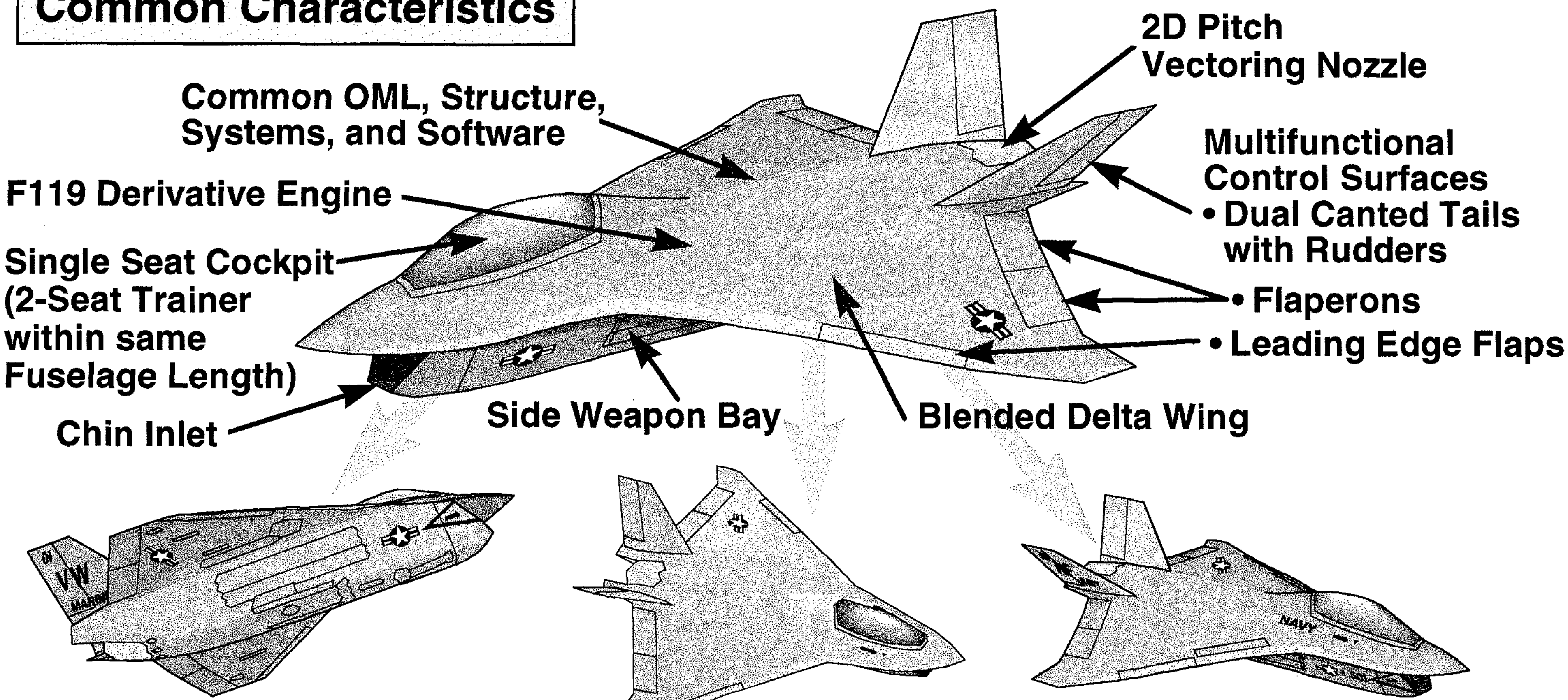
Common Characteristics



STOVL
- Wingtips Removed
- Direct Lift Nozzles

CTOL
- Internal 20mm Gun
- Lightweight Arresting Hook

CV
- Dual Nose Gear, Arresting Hook
- Higher Strength Gear

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Modular Concept

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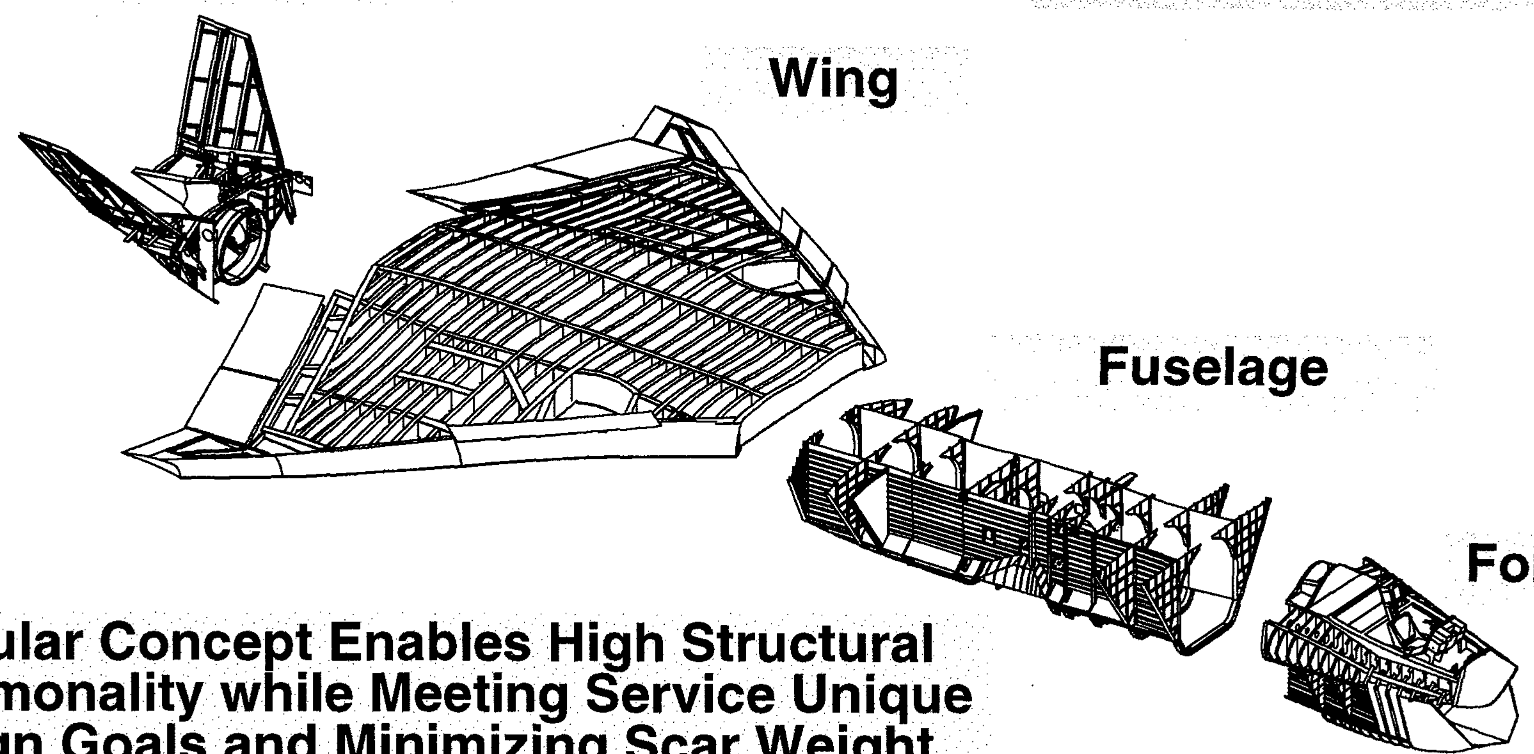
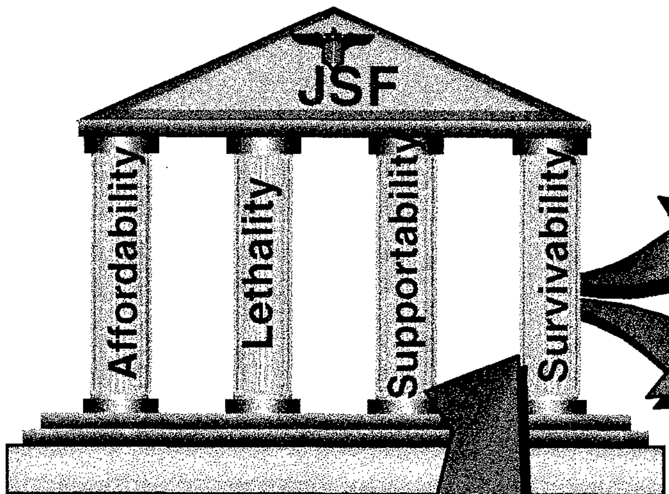
• 4 Major Components



- Modular Concept Enables High Structural Commonality while Meeting Service Unique Design Goals and Minimizing Scar Weight
- Multi-Service Common Engine
- 99-100% Common Cockpit, Avionics, Software, Subsystems

JOINT STRIKE FIGHTER

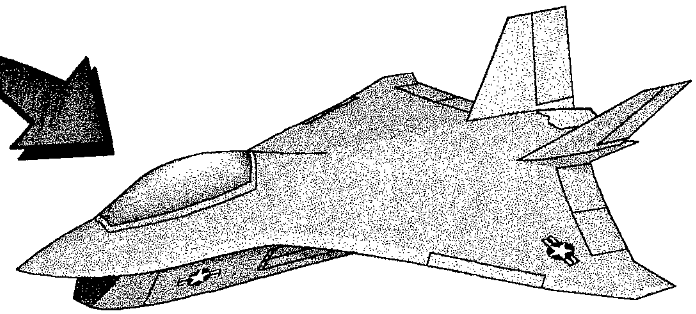
Survivability



Vulnerability
-Redundancy -Shielding -Toughness -Separation -Clustering

Susceptibility
-Speed -Range -Signature -Maneuverability -Altitude

The JSF Configuration is a Balance of Vulnerability and Susceptibility



Survivability is the Capability to Complete the Missions, Return the Aircraft Safety and Rapidly Deploy the Aircraft for the Next Mission

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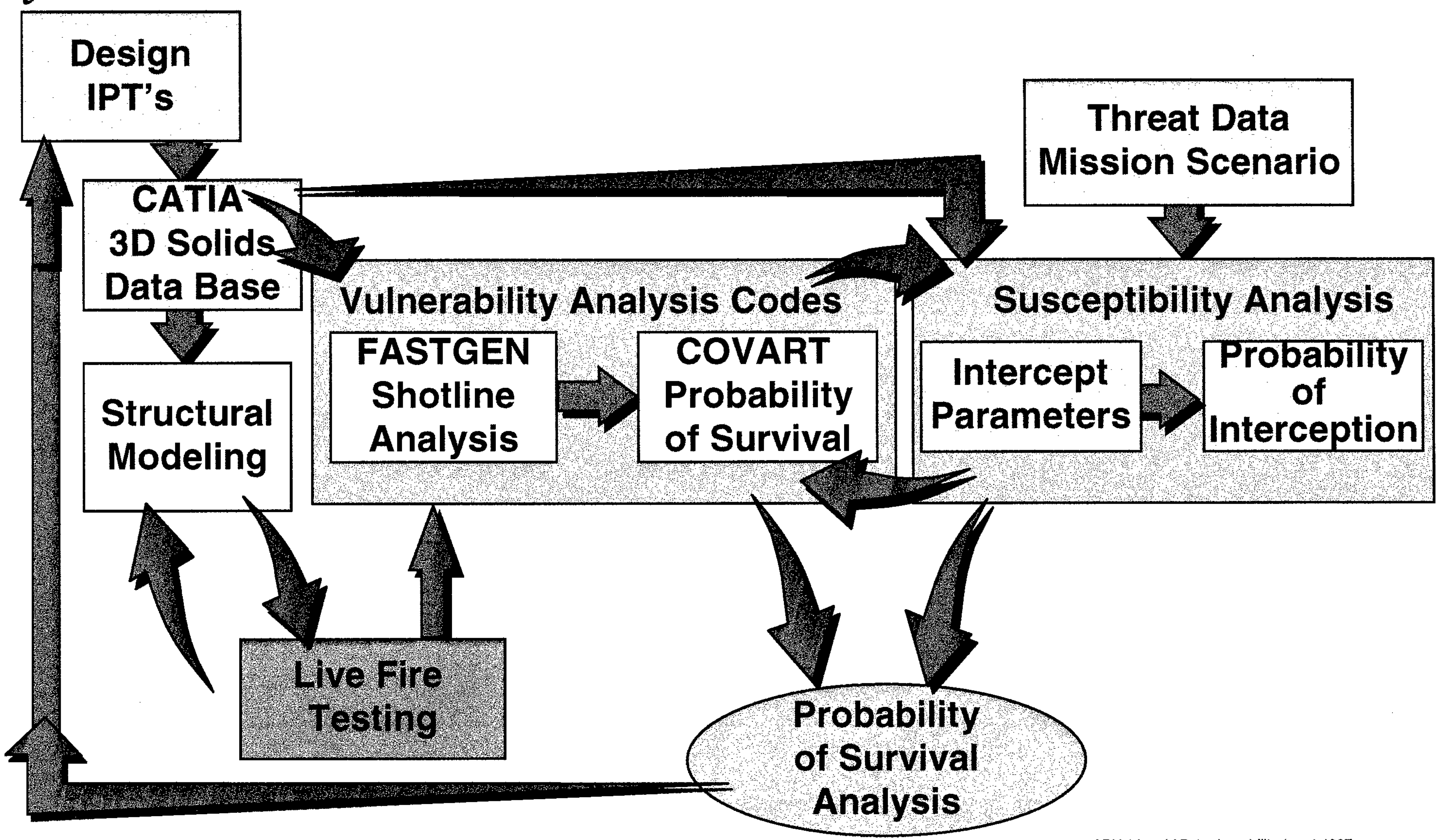
Balance Between Susceptibility and Vulnerability



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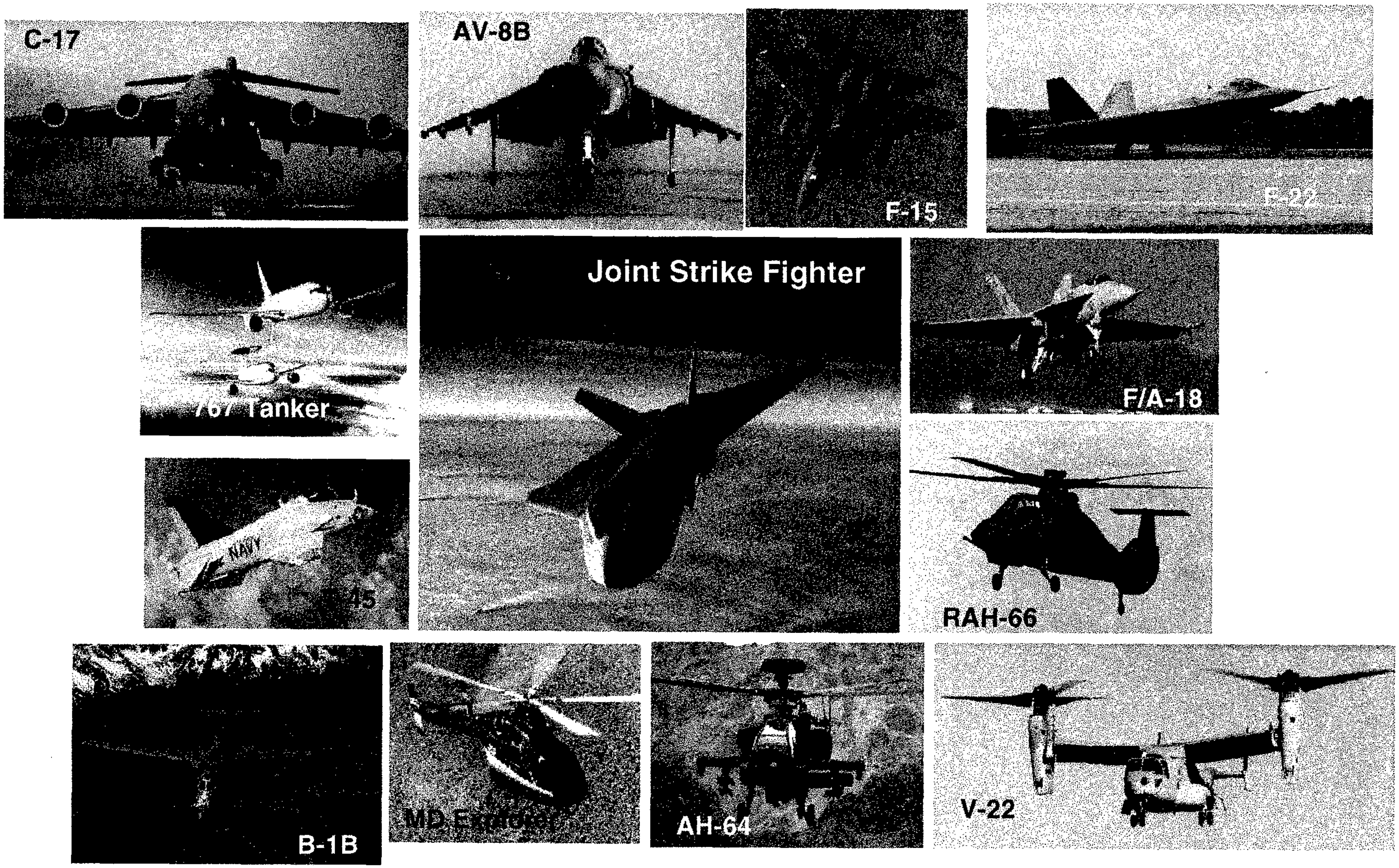
JOINT STRIKE FIGHTER JSF BOEING

Lessons Learned Applied to Boeing's JSF PWSC



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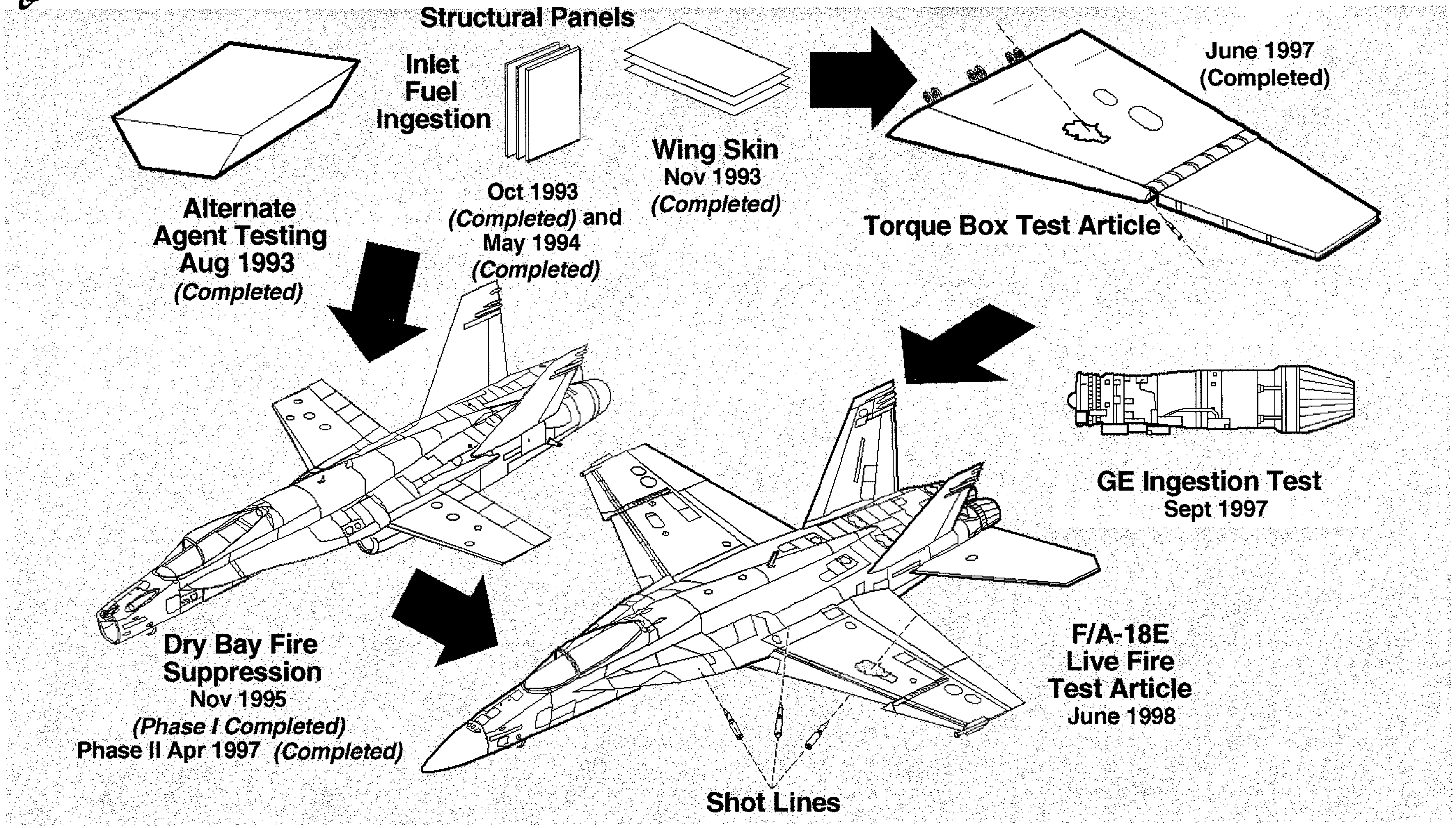
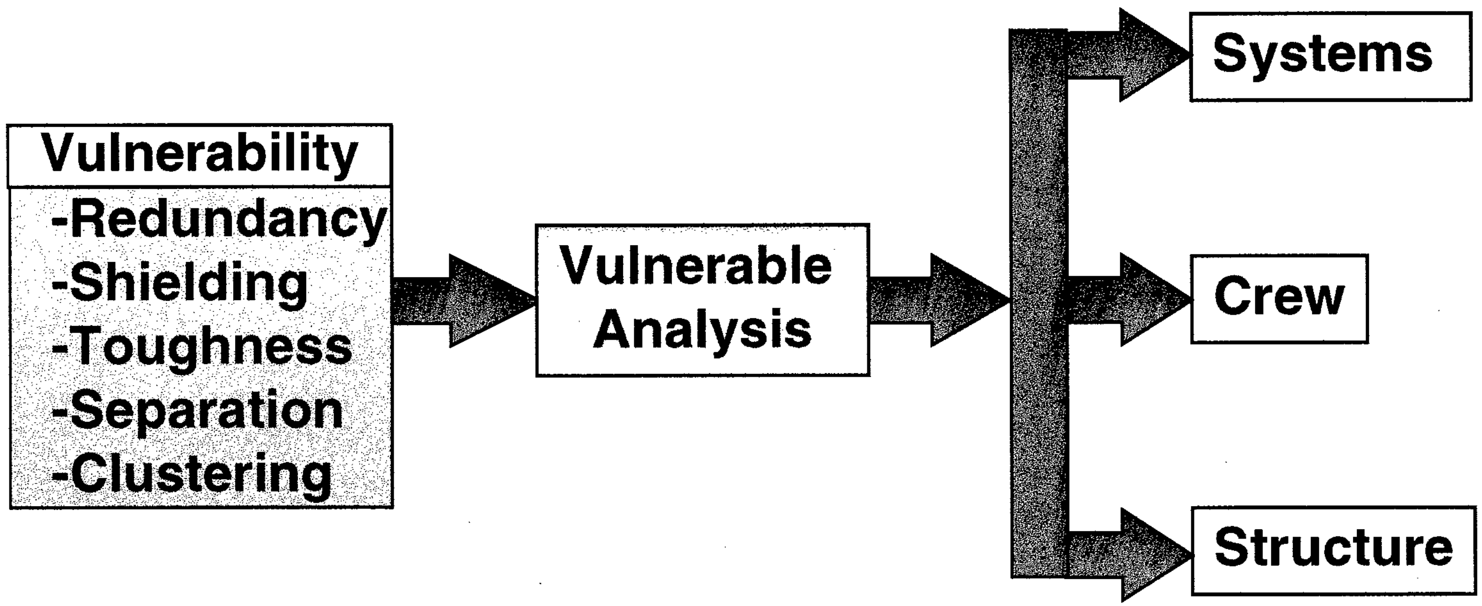
Building Block Approach for Live Fire Testing



JOINT STRIKE FIGHTER

Vulnerability Analysis -Approach



JOINT STRIKE FIGHTER

JSF

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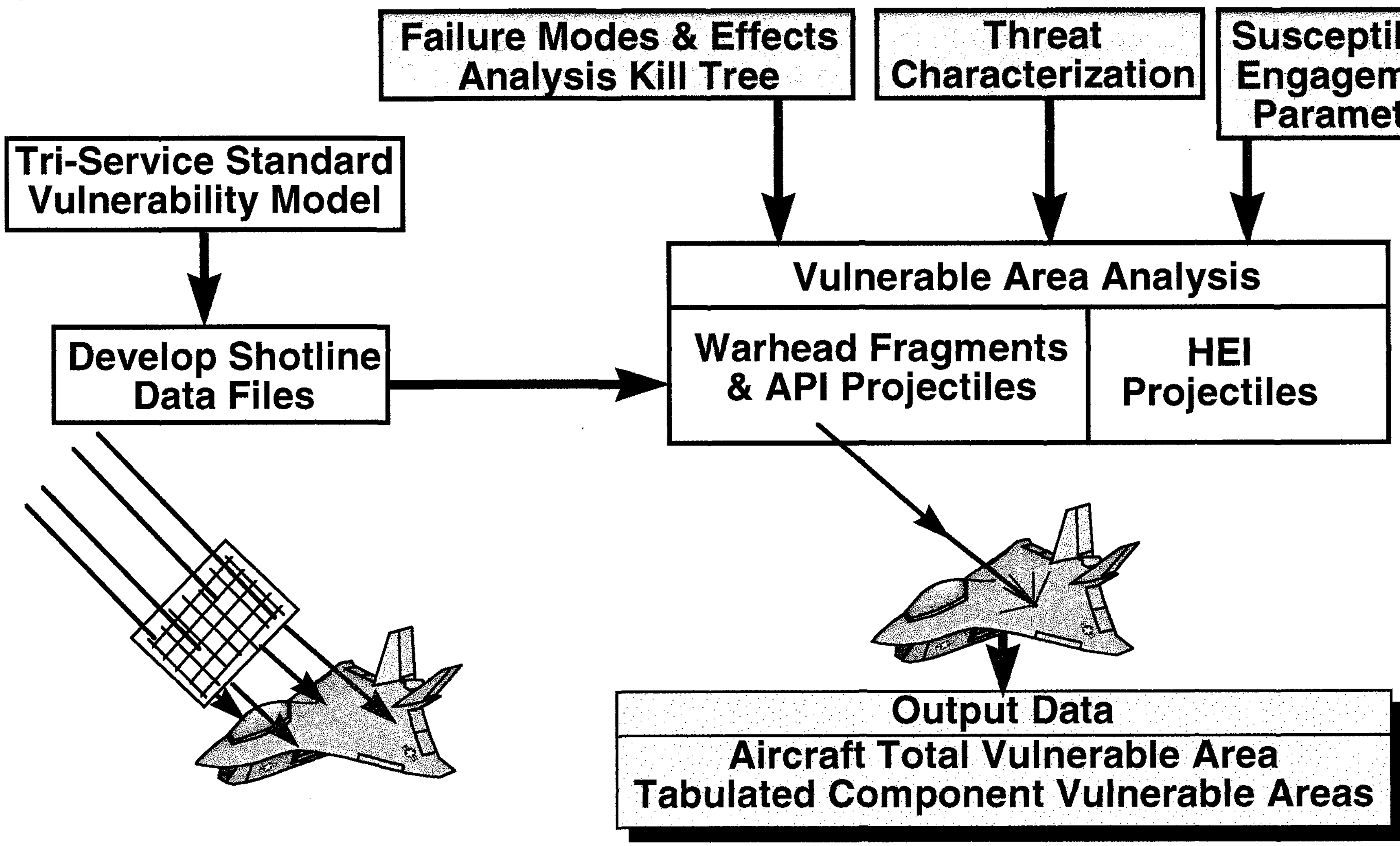
Boeing's Vulnerability Analysis Methods



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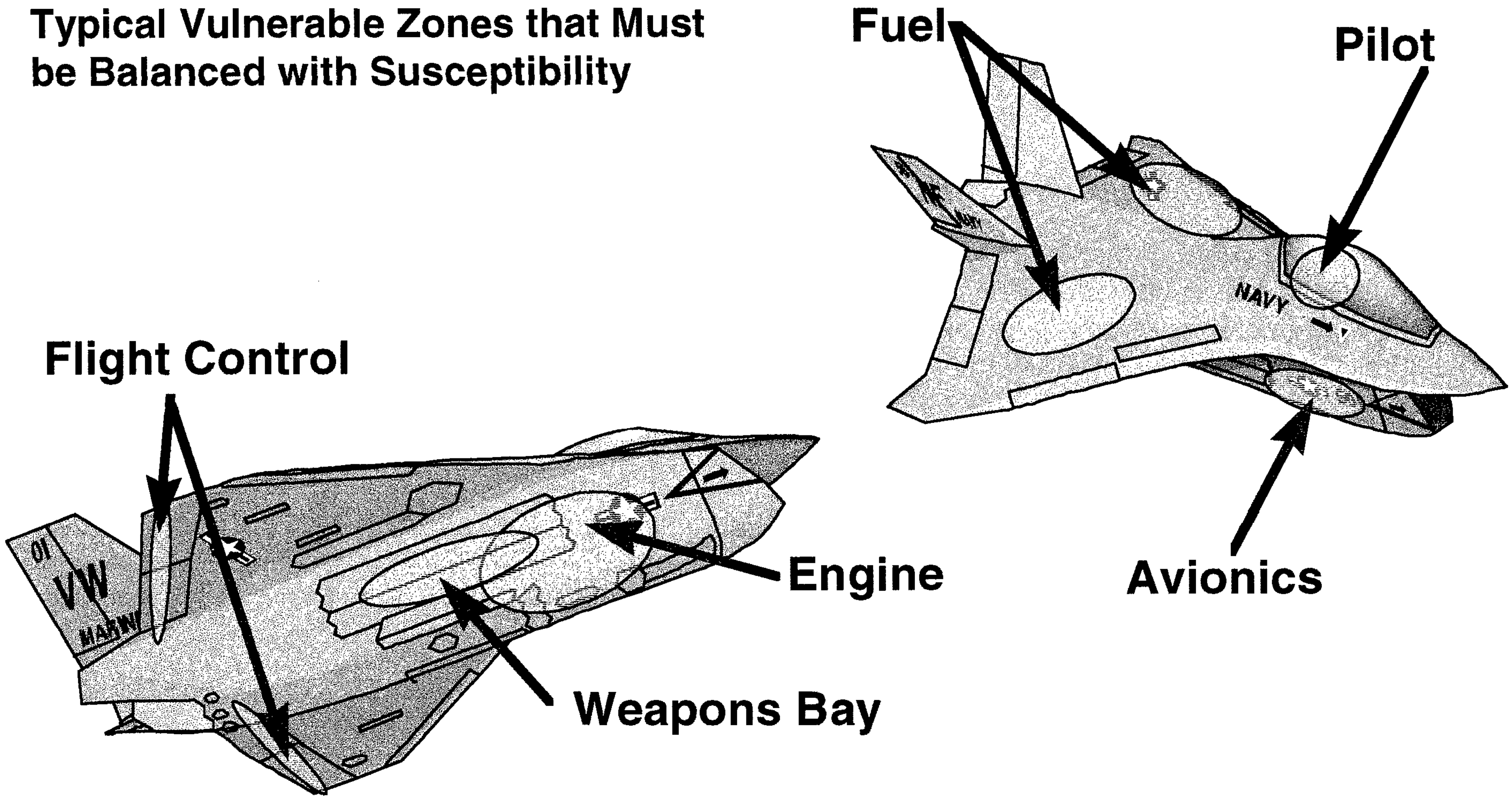
Vulnerable Zones of Aircraft

Typical Vulnerable Zones that Must be Balanced with Susceptibility



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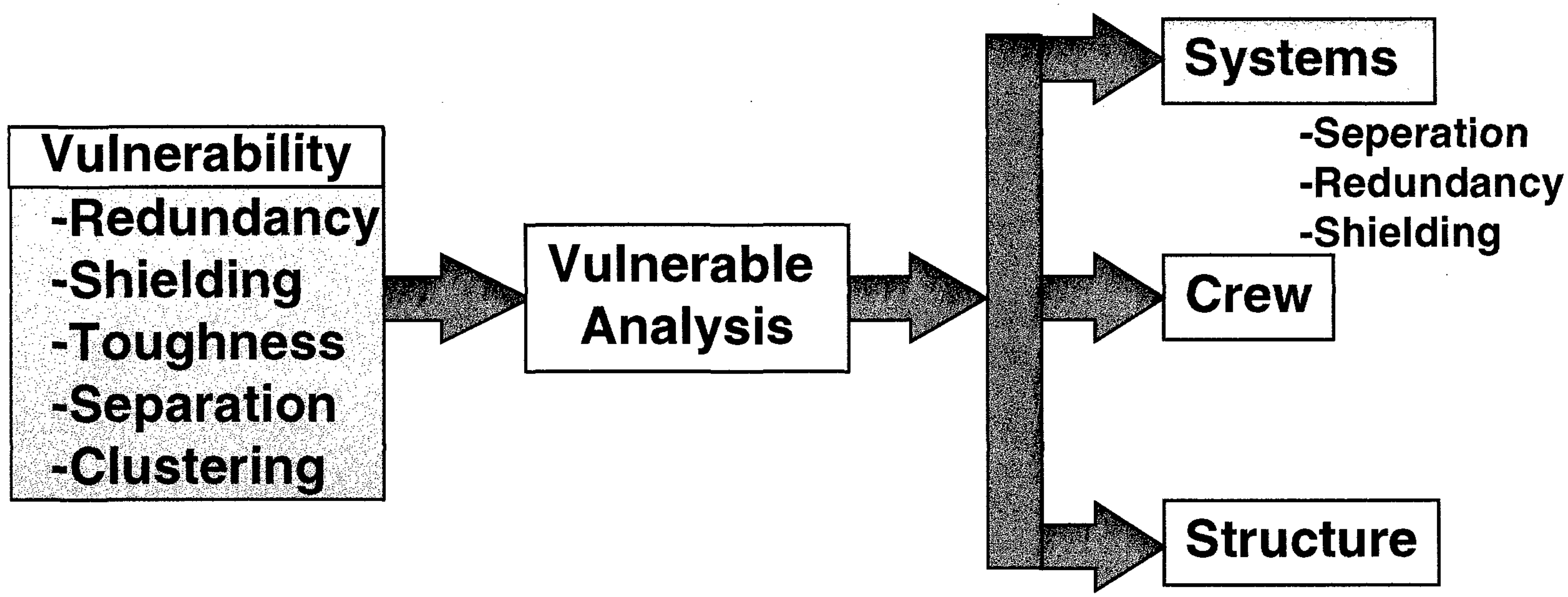
Vulnerability Analysis -Approach



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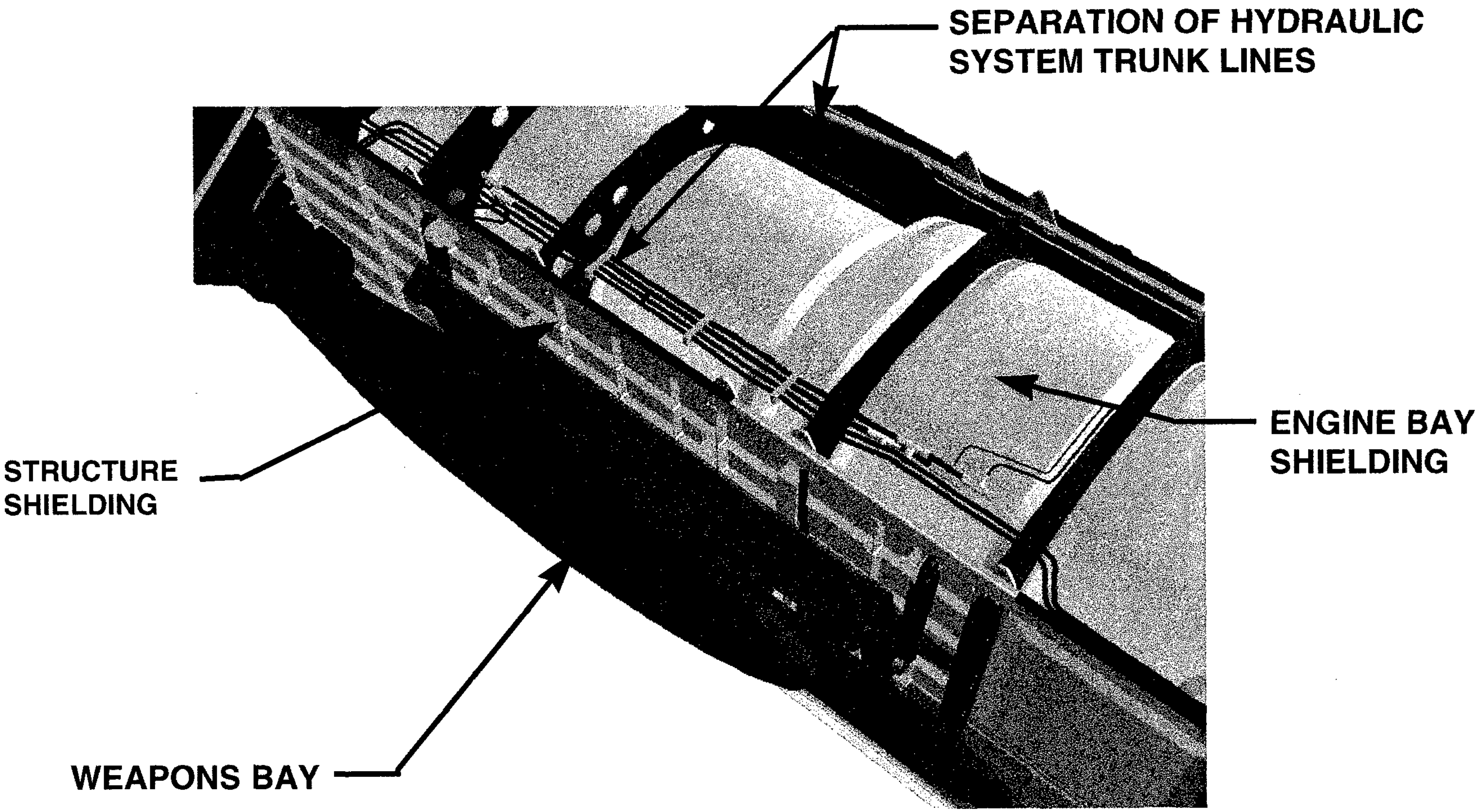
TYPICAL SHIELDING AND SEPARATION



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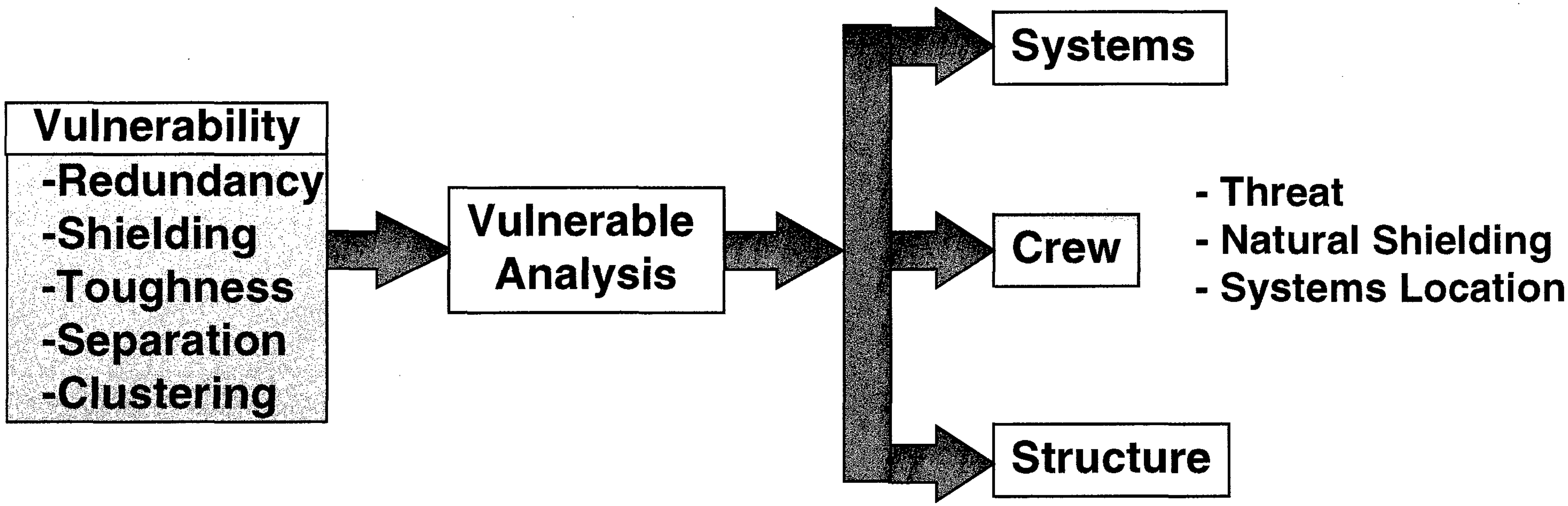
Crew Protection Design Approach



Develop Shotline Format Model Digitally from CATIA Design Model

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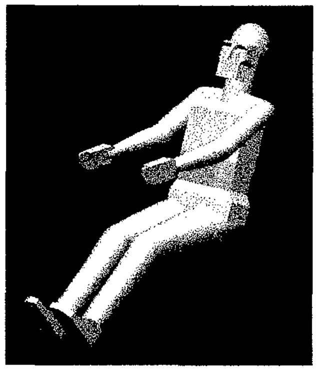
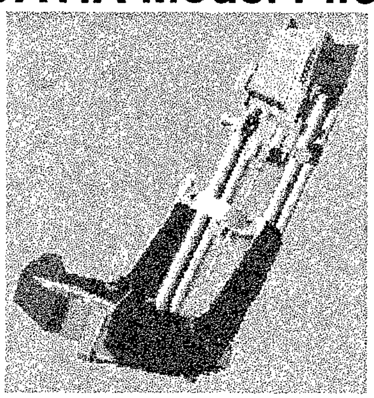
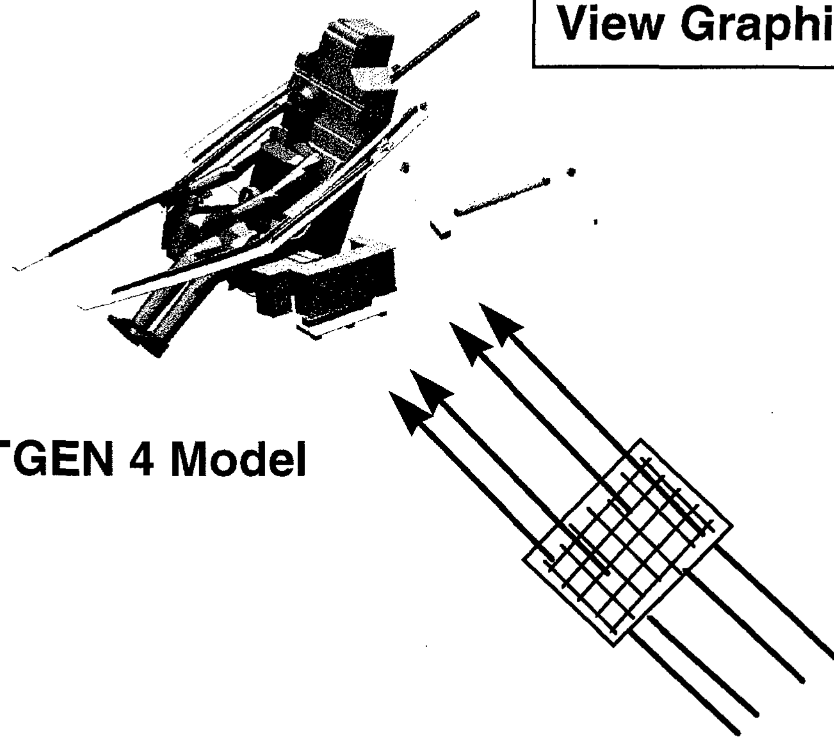
Pilot & Seat Assembly

Aircraft Design → CATIA Models → Convert Data to Shotline Vulnerability Model → Tri-Service Standard Vulnerability Model → View Graphics



CATIA Model Pilot





FASTGEN 4 Model

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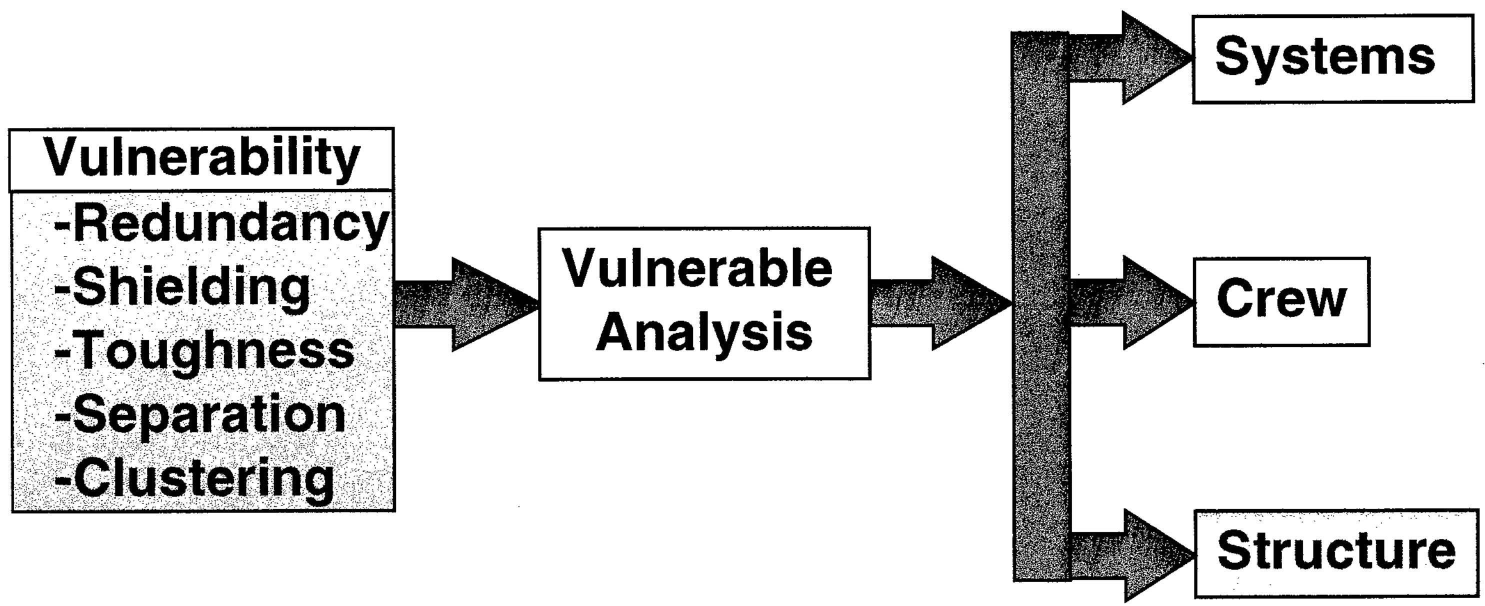
System Design Approach



- Finite Element Modeling
- Redundancy Vs Single Load Path
- Energy Absorption
- Hydraulic Ram

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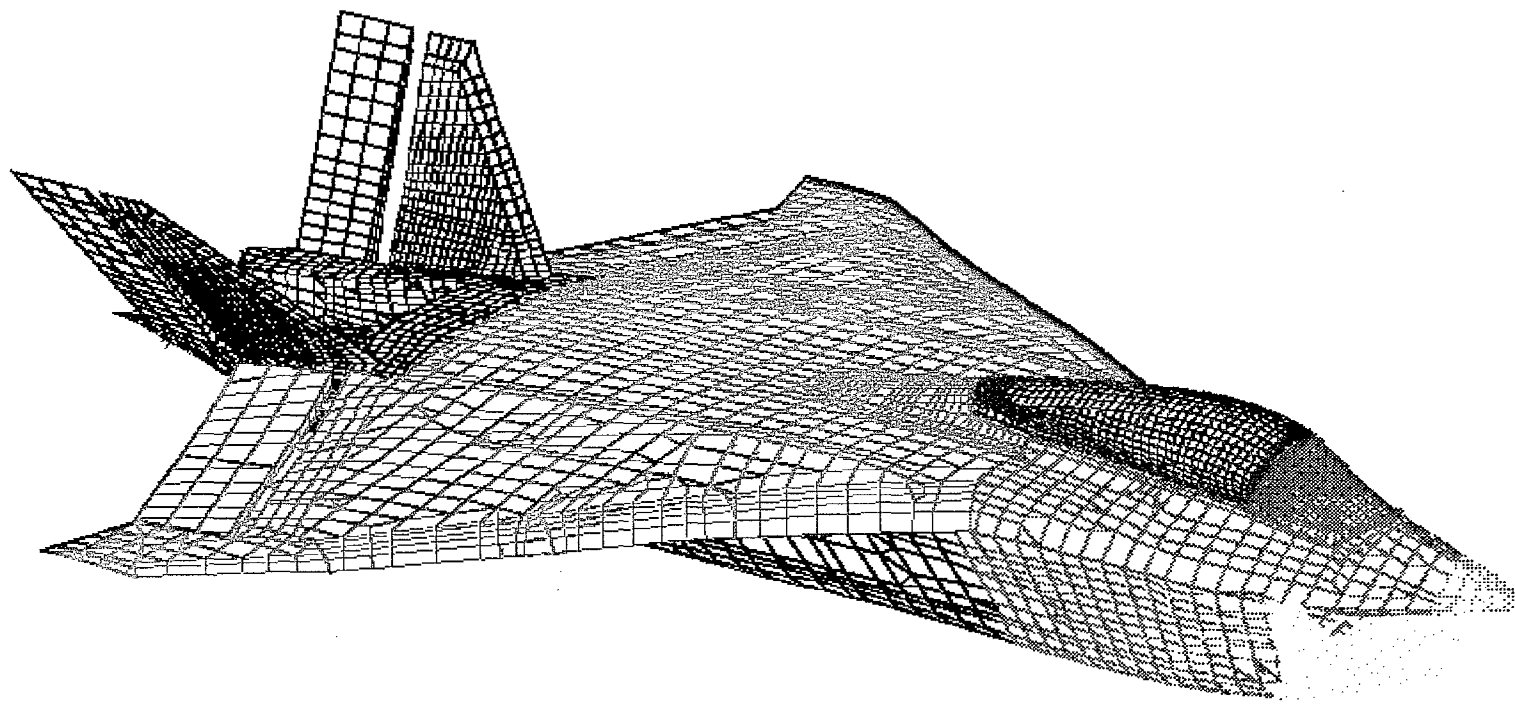
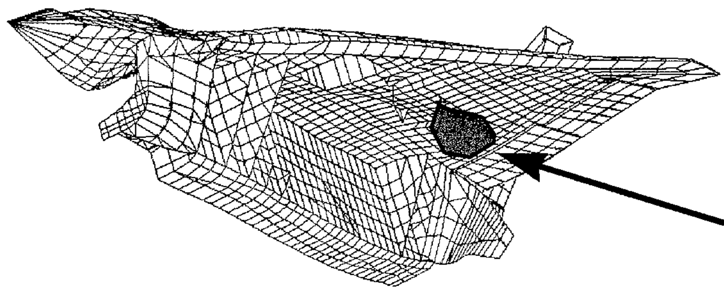
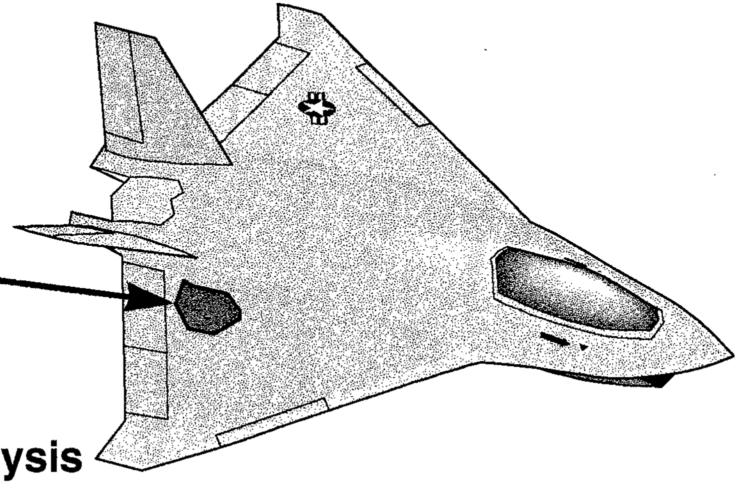
Finite Element Model



JOINT STRIKE FIGHTER

PWSC Wing Structure Vulnerability Analysis





Objective

Characterize Wing Damage from Hydraulic RAM Analysis

Approach:

- Loads – Flight Condition Symmetrical Pull-up at Impact and Residual Strength
- Assume Hydrodynamic Ram Eliminates Internal Spars and Associated Skins
- Spars and Skin Eliminated from FEM Incrementally
- FEM Principal Skin Strains Compared against Wing Material Allowables.

Results

- Number of Spars which can be Lost and Maintain Partial Structural Integrity

Analysis used prior to live fire testing

Hydraulic RAM Structural Response

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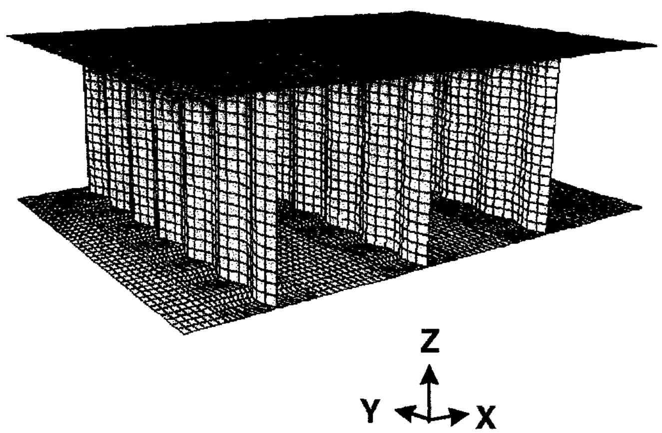
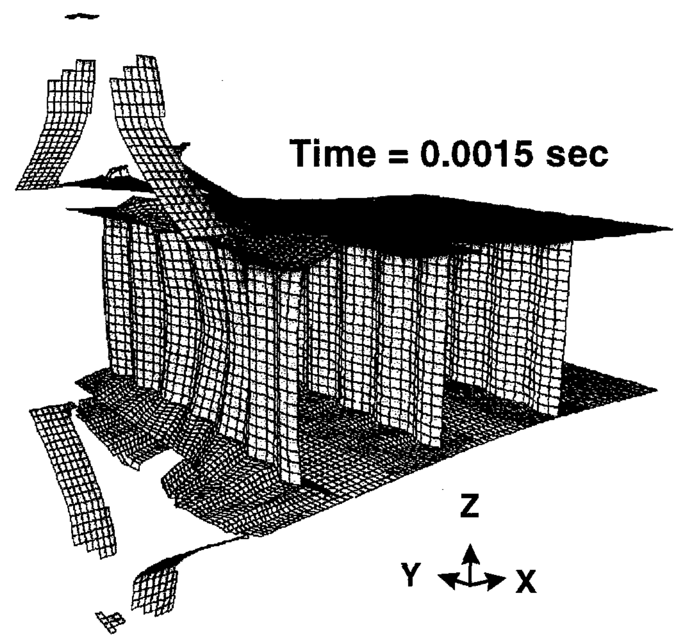
Wing Box Structure
Energy Equivalent to 30 mm HEI

Time = 0 sec



Time = 0.0015 sec



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Hydraulic Ram Shock Pressures

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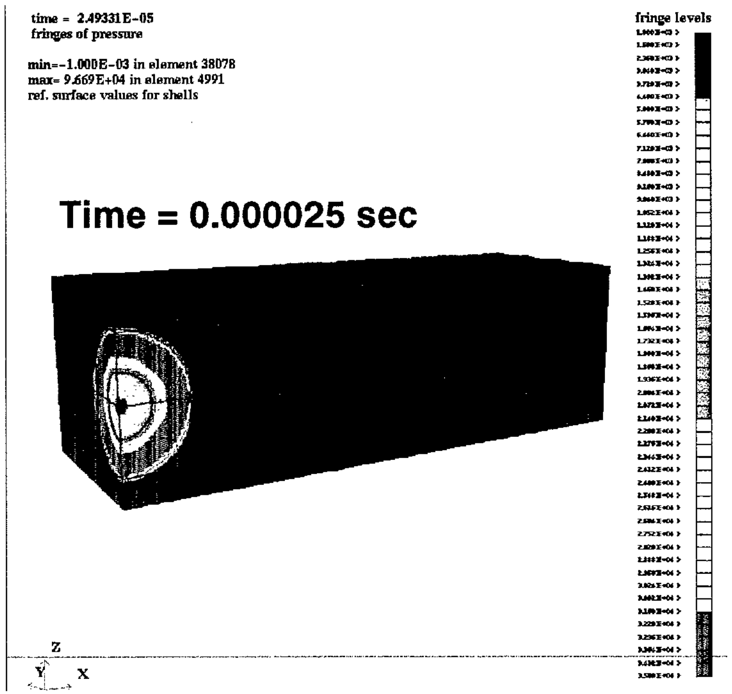
Wing Box Structure
Energy Equivalent to 30 mm HEI



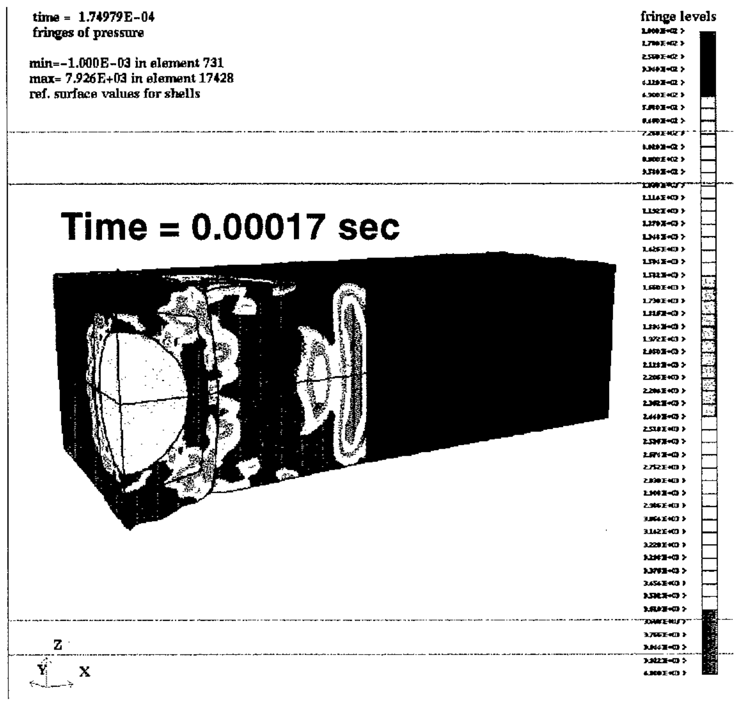
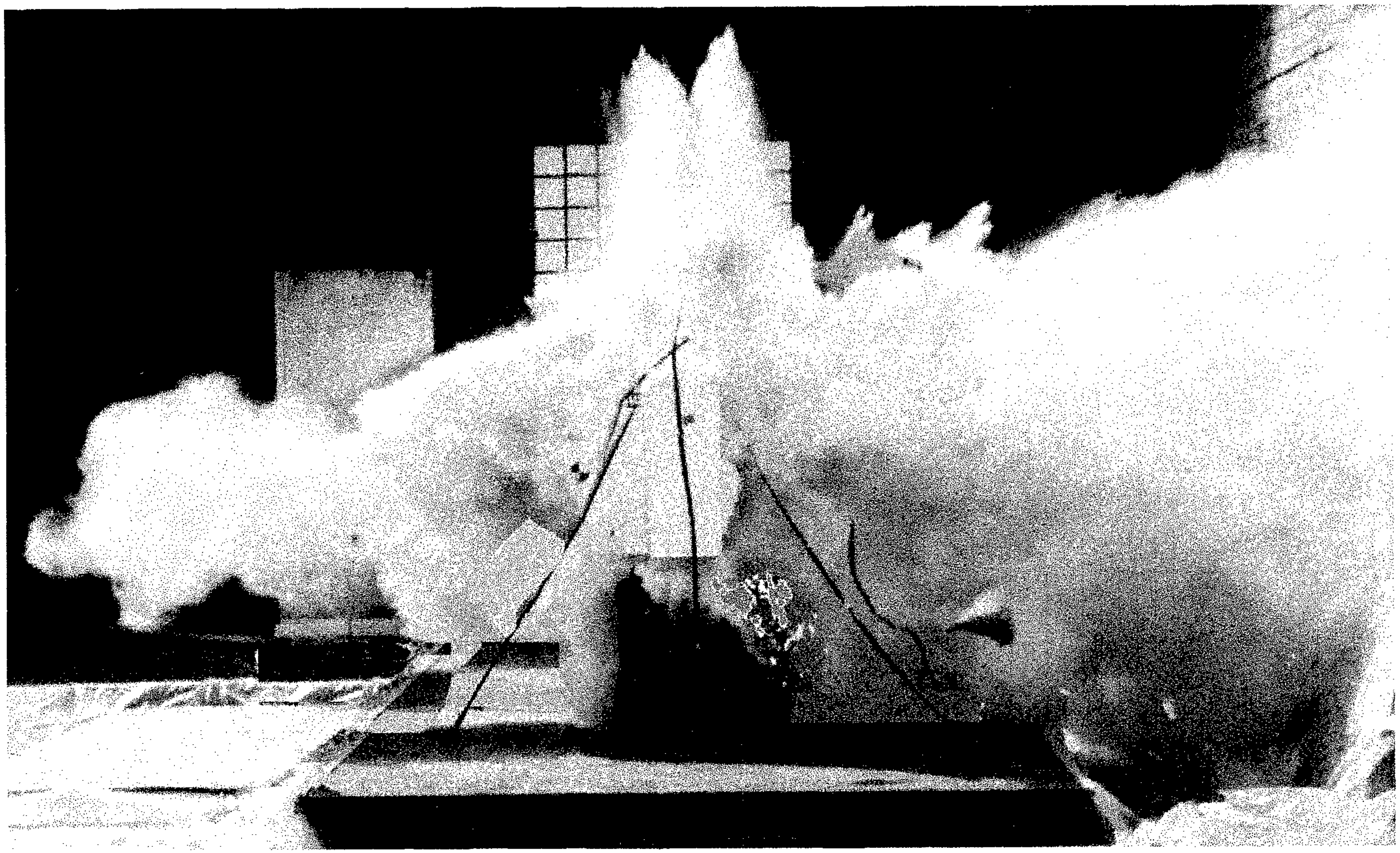


Photo of Event



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JSF

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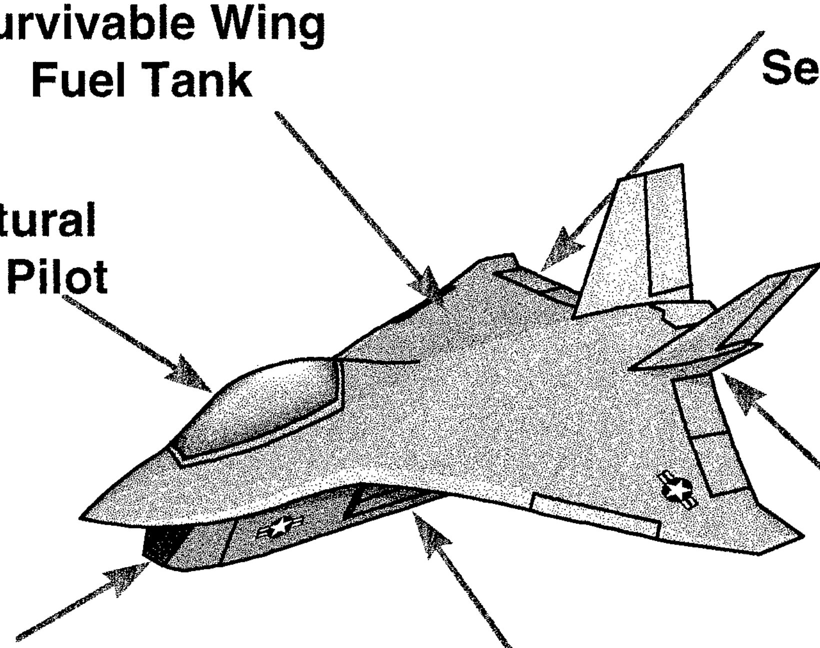
Results of Analysis and Demonstration Testing on PWSC Design



Summary

- JSF objective of Affordability
- Boeing's Approach is to Balance Vulnerability and Susceptibility
- Tools Such as 3D Solids Models, Finite Element Analysis, and Computational Fluid Dynamics will reduce the cost of the JSF Development
- Modeling, Simulation and Testing will reduce risk for the JSF Design
- Analysis, verified by component testing, will justify wavier from full scale "live fire law" test.

BOEING®

Space System Vulnerability to Orbital Debris Penetration

Dr. Joel Williamsen
NASA/MSFC

A Poster Presentation
to the
ADPA/NSIA/AIAA

Aircraft Survivability Conference

Monterey, CA
October 21-23, 1997

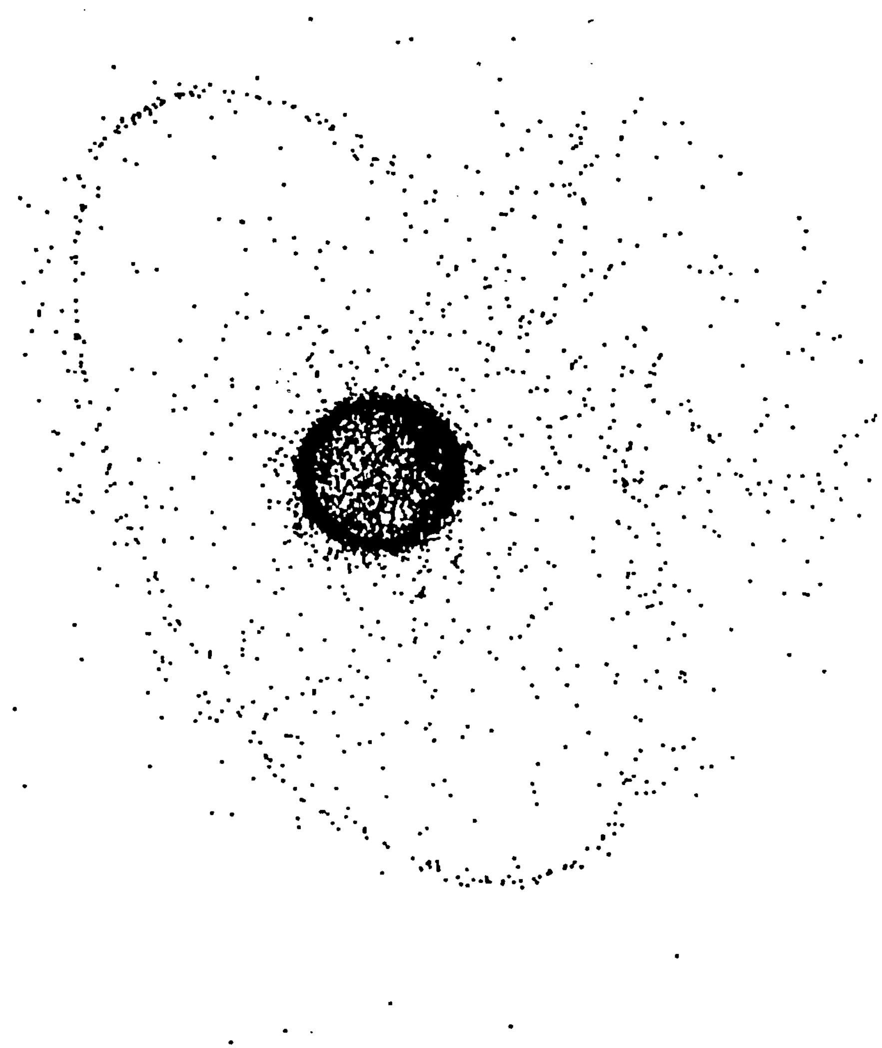
National Aeronautics and Space Administration
George C. Marshall Space Flight Center

Joel E. Williamsen
Space System Survivability
Meteoroid/Orbital Debris Impact

ED 52
Stru al Development Branch
MSFC, AL 35812

Work: (205) 544-7007
Home: (205) 882-0651

- **Orbital debris (space junk) has grown explosively over the last four decades.**
  - Now over 2,000,000 kg of mass in low earth orbit (LEO--up to 2000 km) vs. 70 kg of meteoric material.
  - 100,000 LEO objects over 1 cm diameter.
  - Average crossing (impact) velocity of orbital debris--8.7 km/sec.
  - Approxiamtely 70% aluminum, 30% plastic, steel, copper wiring, etc.



- **Probability of impact increases with exposure area and time.**
  - International Space Station has over 1000 square meters of exposed area and a design life of 15 years.
  - LEO satellite constellations (Iridium) have large cumulative exposed areas and exposure times.
- **Orbital Debris is highly directional--approaching from the "front" and "sides" of a stable LEO spacecraft.**

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Structures and Dynamics Laboratory

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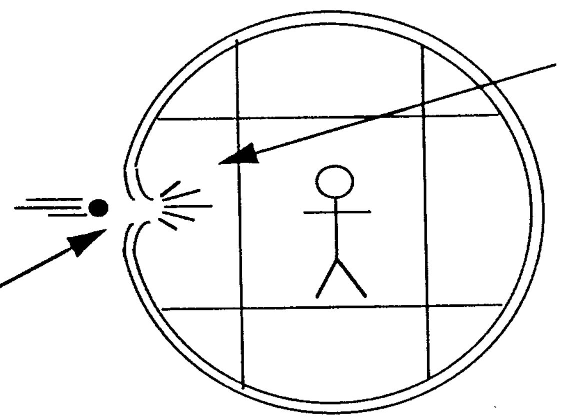
ED52 STRUCTURAL DEVELOPMENT BRA NCH

ORBITAL DEBRIS RISK MITIGATION

For a single impact,* $P_{loss} = P_{impact} \times P_{\frac{penetration}{impact}} \times P_{\frac{loss}{penetration}}$



Reduce P_{impact}

- Environmental Definition

→ **Debris Reduction, Tracking, & Avoidance**

Reduce $P_{penetration/impact}$

- Penetration
- Ricochet
- Spallation

→ **Augmented Shields and Materials**

Analysis Tool: BUMPER

Reduce $P_{loss/penetration}$

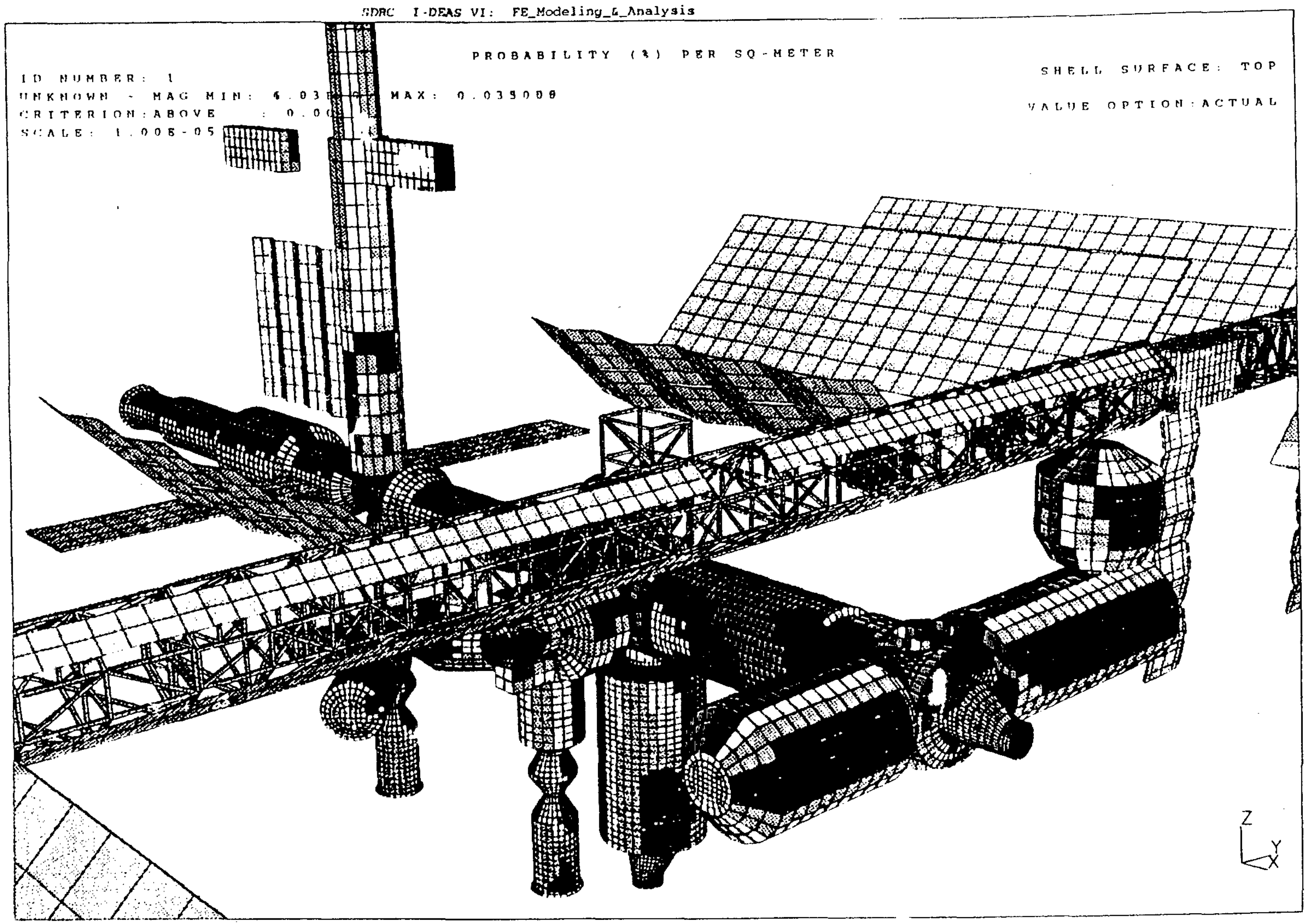
- Critical Cracking
- Thrust Hazard
- Critical Equipment Loss
- Injury Loss
- Hypoxia
- Critical Module Depressurization

→ **Modify Design and Ops:**

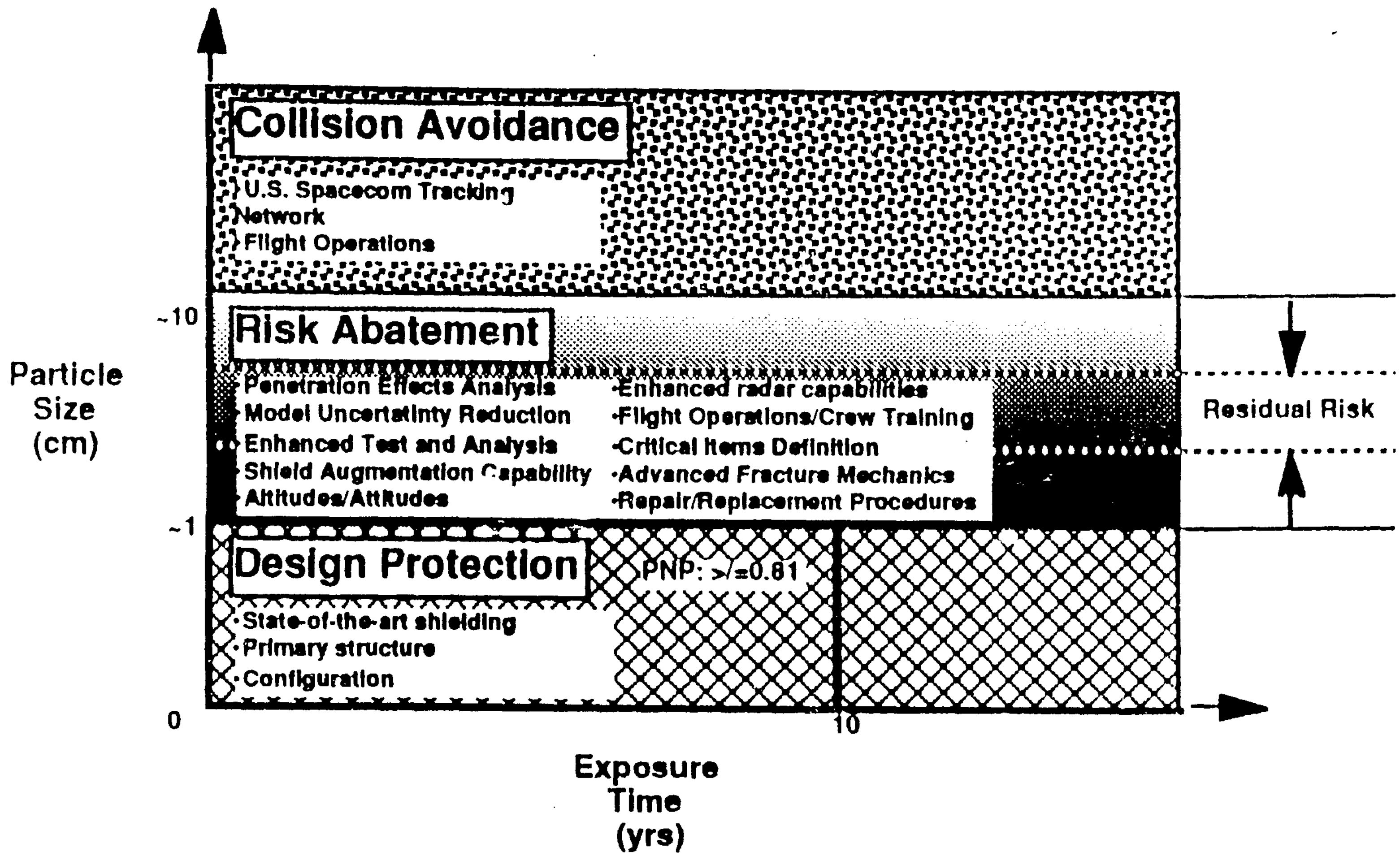
- Equipment Locations
- Hatches Open/Closed
- Crew Position in Modules
- Sealing/Repair Strategies
- Internal Spall Blanket

Analysis Tool: MSCSurv
(Manned Spacecraft Crew Survivability)

* Probability of loss due to one or more impacts = $P_{loss} = 1 - \exp(-N_{impacts} \times P_{penetration/impact} \times P_{loss/pen})$.



Probability of Orbital Debris Impact
Highest Probability Areas in Red



M/OD Strategic Plan

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
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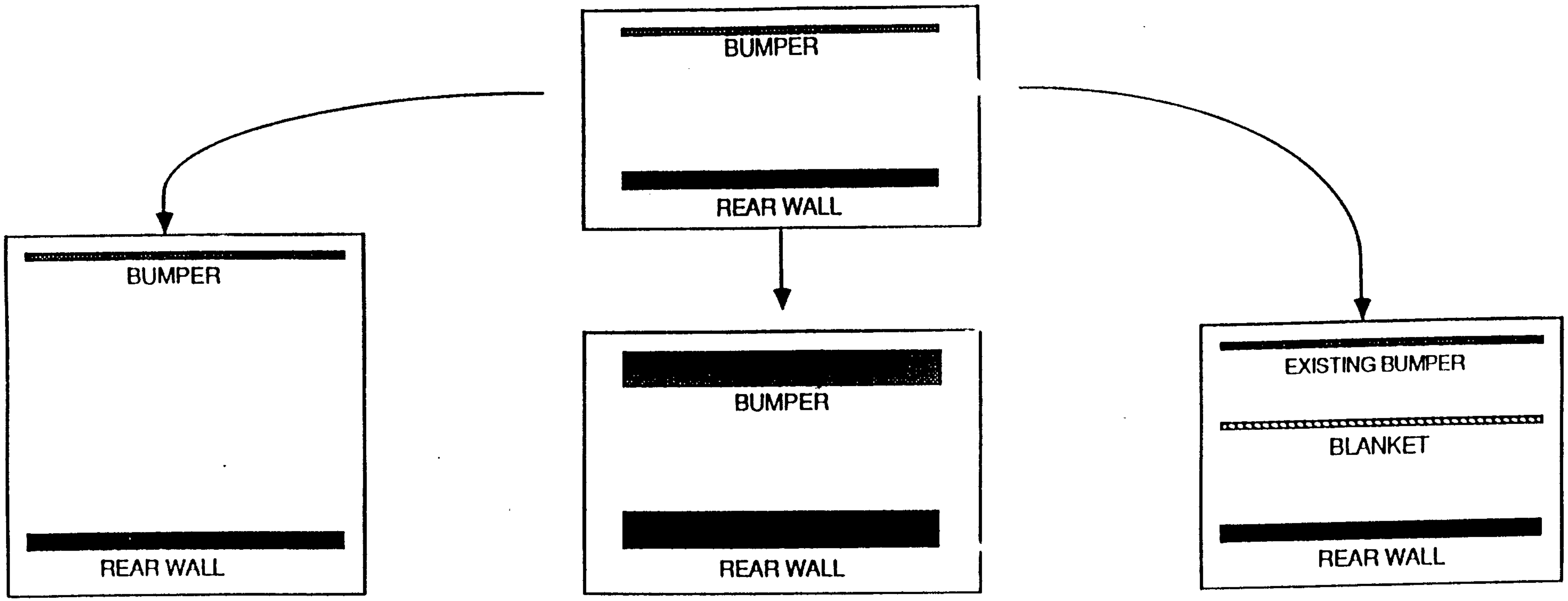
Structures Division

SPACECRAFT SURVIVABILITY IN THE ORBITAL DEBRIS ENVIRONMENT

J. Williamsen
May 25, 1993

THREE WAYS TO IMPROVE BASELINE SHIELDING



LONGER STANDOFF

- MOST WEIGHT EFFICIENT
- DIFFICULT TO PACKAGE INTO ORBITER

THICKER BUMPER AND WALL

- LEAST WEIGHT EFFICIENT
- EASIEST TO IMPLEMENT

ADD LAYERS OF MATERIALS

- MODERATELY EFFICIENT
- POSSIBLE TO IMPLEMENT ON EXISTING DESIGN

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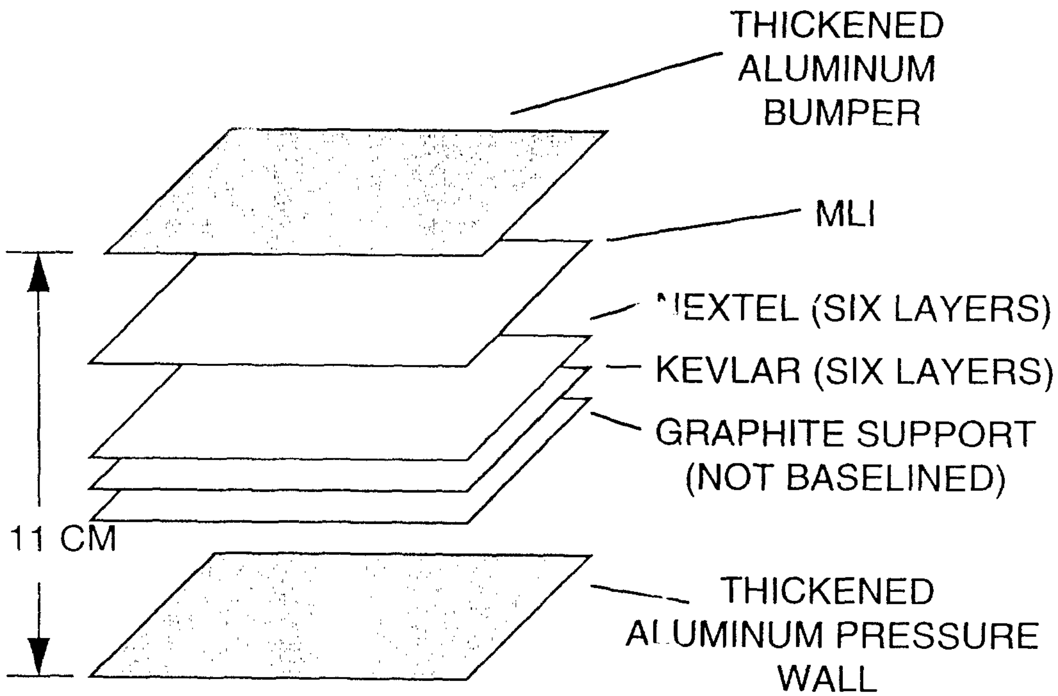
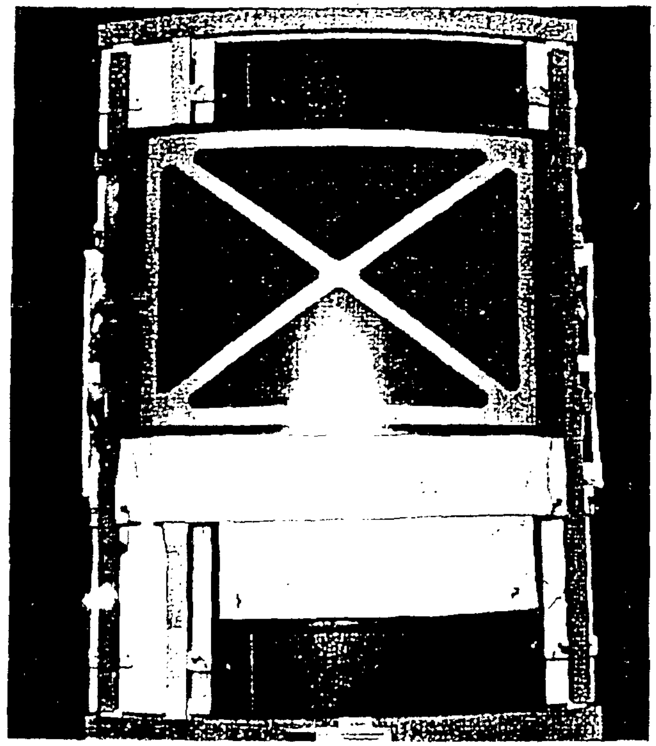
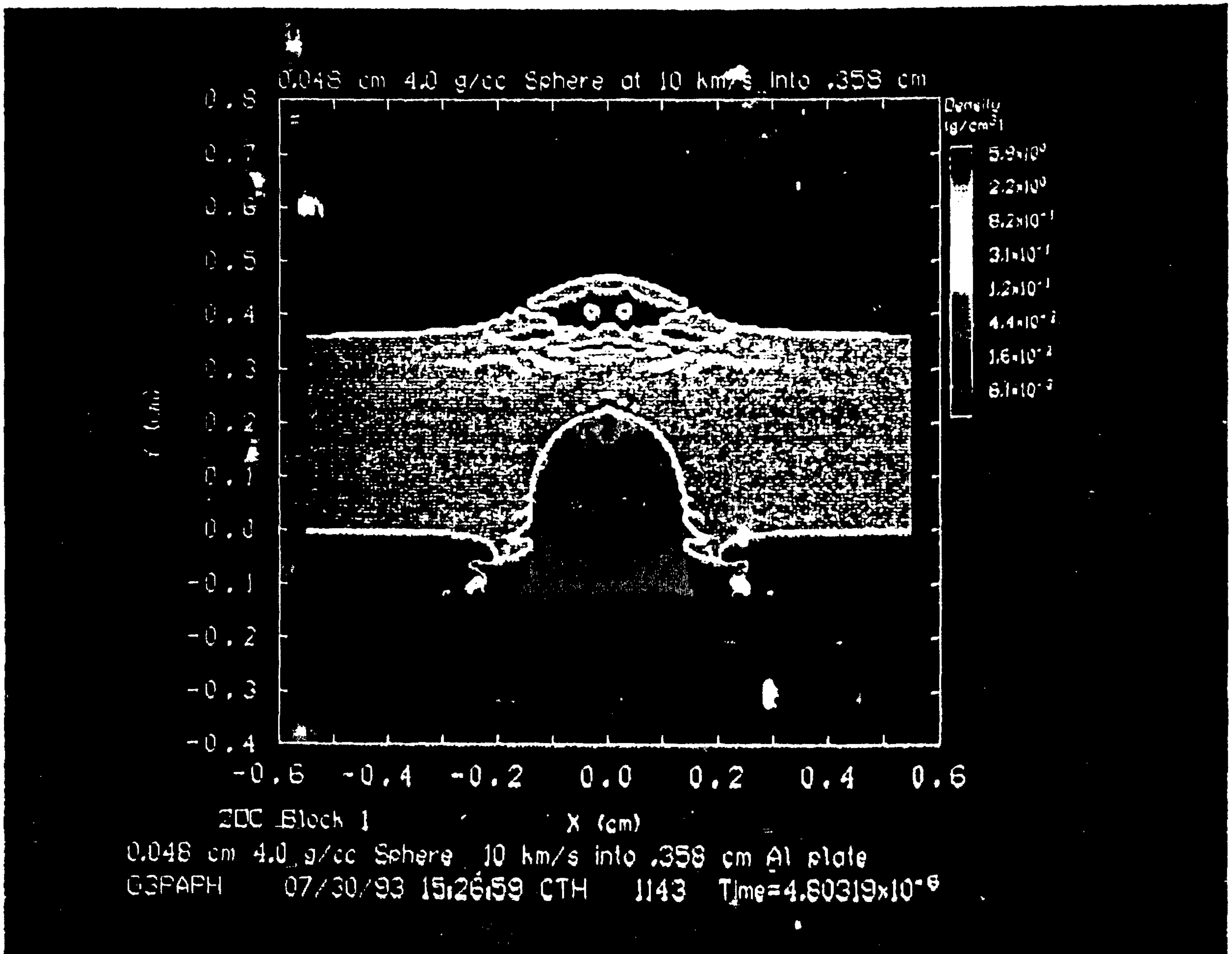
ED52 STRUCTURAL DEVELOPMENT BRANCH

ENHANCED MANNED MODULE SHIELDING





- IN-HOUSE NASA DEVELOPMENT (WITH JSC) FOR USE IN U.S. LAB, HAB, AIRLOCK.
- DEFEATS 10X MORE MASSIVE PARTICLES (ON AVERAGE)THAN BASELINE SHIELD.
- NOW PLANNED FOR USE ON NASDA, ESA MODULES. RSA ALSO EXAMINING USE FOR FGB.

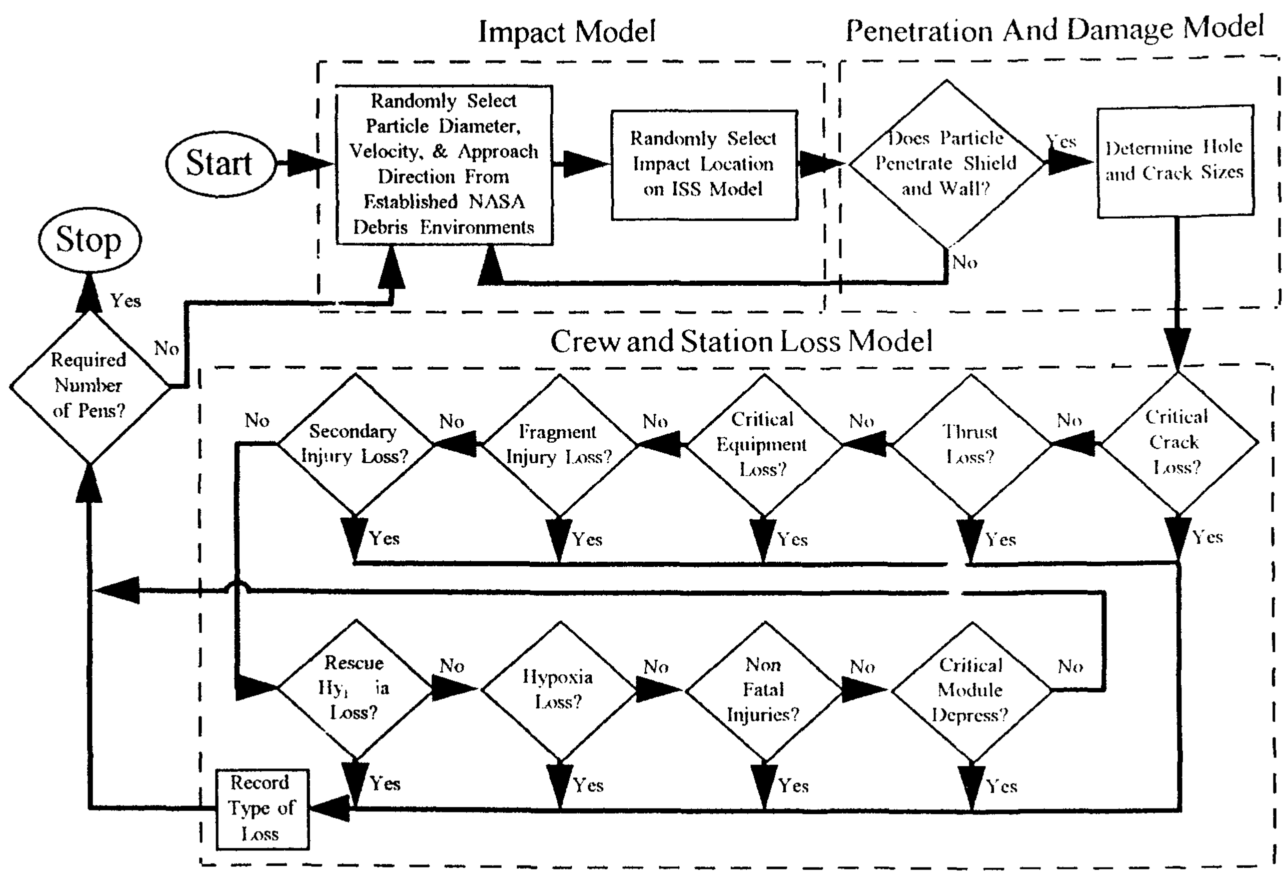


0.048 cm 4.0 g/cc Sphere at 10 km/s Into .358 cm
Density (g/cm³)
5.9×10⁰
2.2×10⁰
8.2×10⁻¹
3.1×10⁻¹
1.2×10⁻¹
4.4×10⁻²
1.6×10⁻²
6.1×10⁻³
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
X (cm)
2DC Block 1
0.048 cm 4.0 g/cc Sphere 10 km/s into .358 cm Al plate
G3PAPH 07/30/93 15:26:59 CTH 1143 Time=4.80319×10⁻⁶

MSCSurv Flow Chart

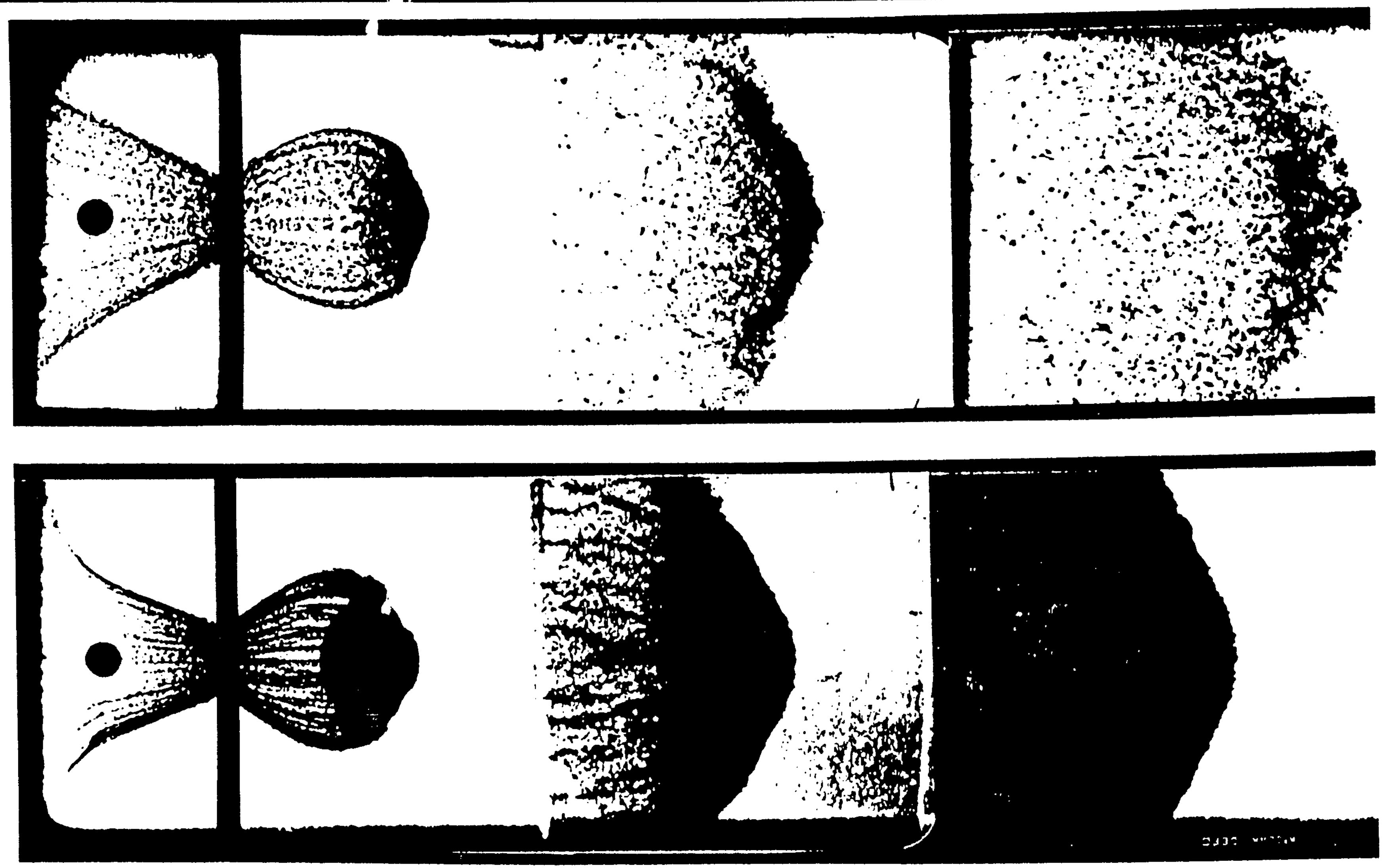
J. Williamsen
17 March 1997

The Manned Spacecraft Crew Survivability (MSCSurv) computer program computes the probability of critical failure following orbital debris penetration.



National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Structures and Dynamics Laboratory
Structures Division

RADIOGRAPHS OF PROJECTILE/TARGET DEBRIS CLOUDS FOR 7 AND 11 km/s IMPACTS



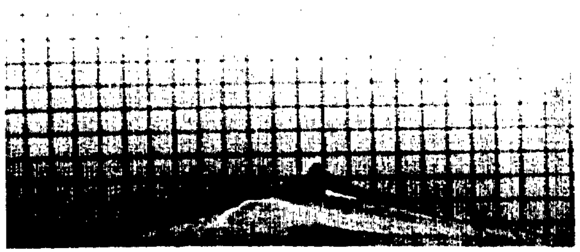
BJORKMANM / 2–8260 / ASAP / 6 / 25 MAY 1993

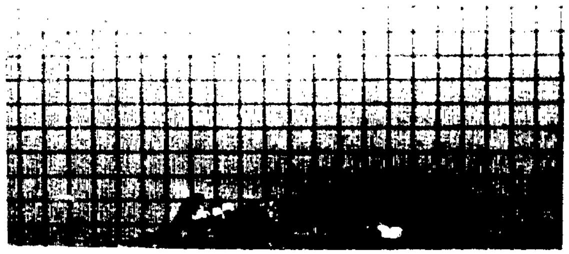
Improving Space Station Survivability Through Module Repair and Shield Augmentation

INTERNATIONAL SPACE STATION

MSFC

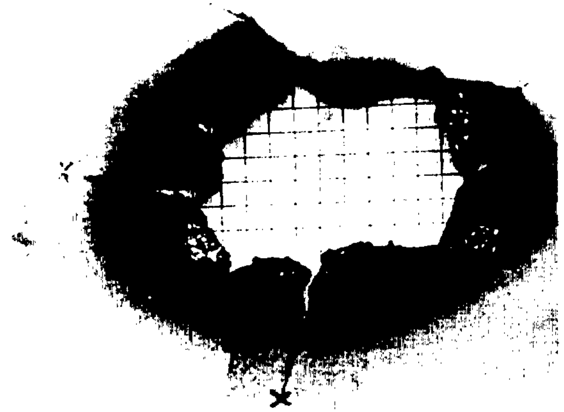
Space Station Pressure Wall Holes Following Hypervelocity Penetration





MSFC #1542 2-1-94
PROJ: 0.375" 3" STD OFF
REAR WALL: 0.125" 2219-T87
VELOCITY: 6.61 km/sec
45° REAR

MSFC 1539 12-3-93
PROJ: 0.250" Al
REAR WALL: 0.080" 6061-T6
45° FRONT



MSFC #1504 7/27/93
PROJ: 0.25" 304 ST. STEEL
REAR WALL: 0.125" 2219-T87
0° REAR

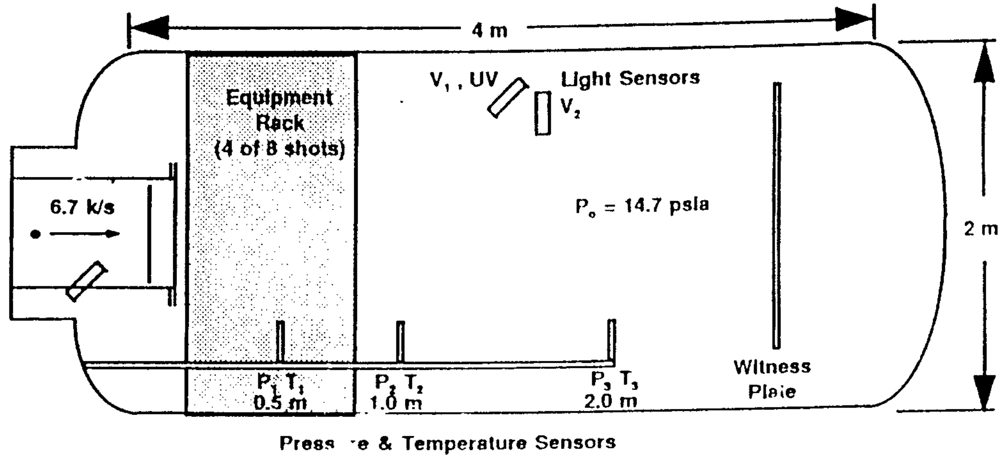
Quantifying and Enhancing Space Station Safety Following Orbital Debris Penetration

Manned Module Internal Effects Following A Penetration

MSFC - University of Alabama in Huntsville

- Eight tests measuring:
  - Overpressure
  - Flash intensity
  - Temperature rise
  - Fragment dispersion.
- Determines effects of:
  - Projectile energy
  - Shield type
  - Internal equipment
  - Spall blankets

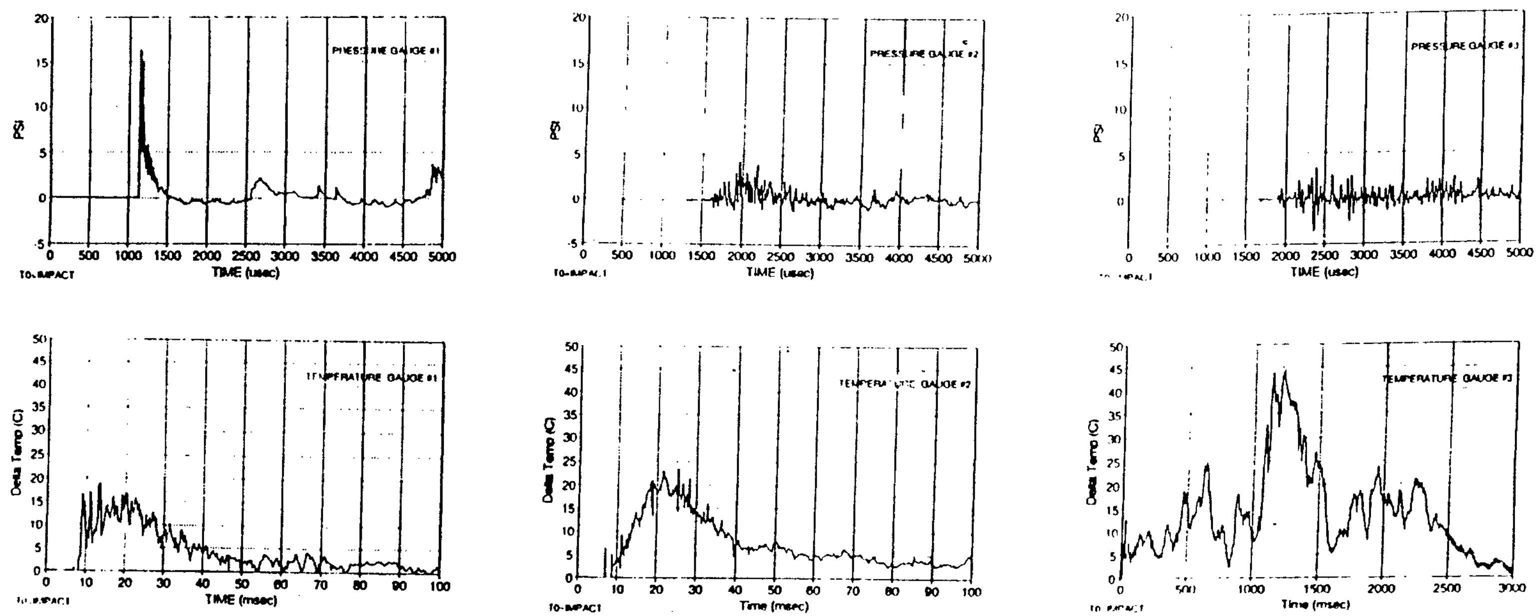
on hazard levels experienced by crew members.



Overpressure

Test #1 7/18/94
Dia = 0.52 in.
Vel = 6.7 k/s
U.S. Lab Whipple Shield
No Internal Equipment

Temperature Rise



Quantifying and Enhancing Space Station Safety Following Orbital Debris Penetration

INTERNATIONAL SPACE STATION

MSFC

Thrust Hazard

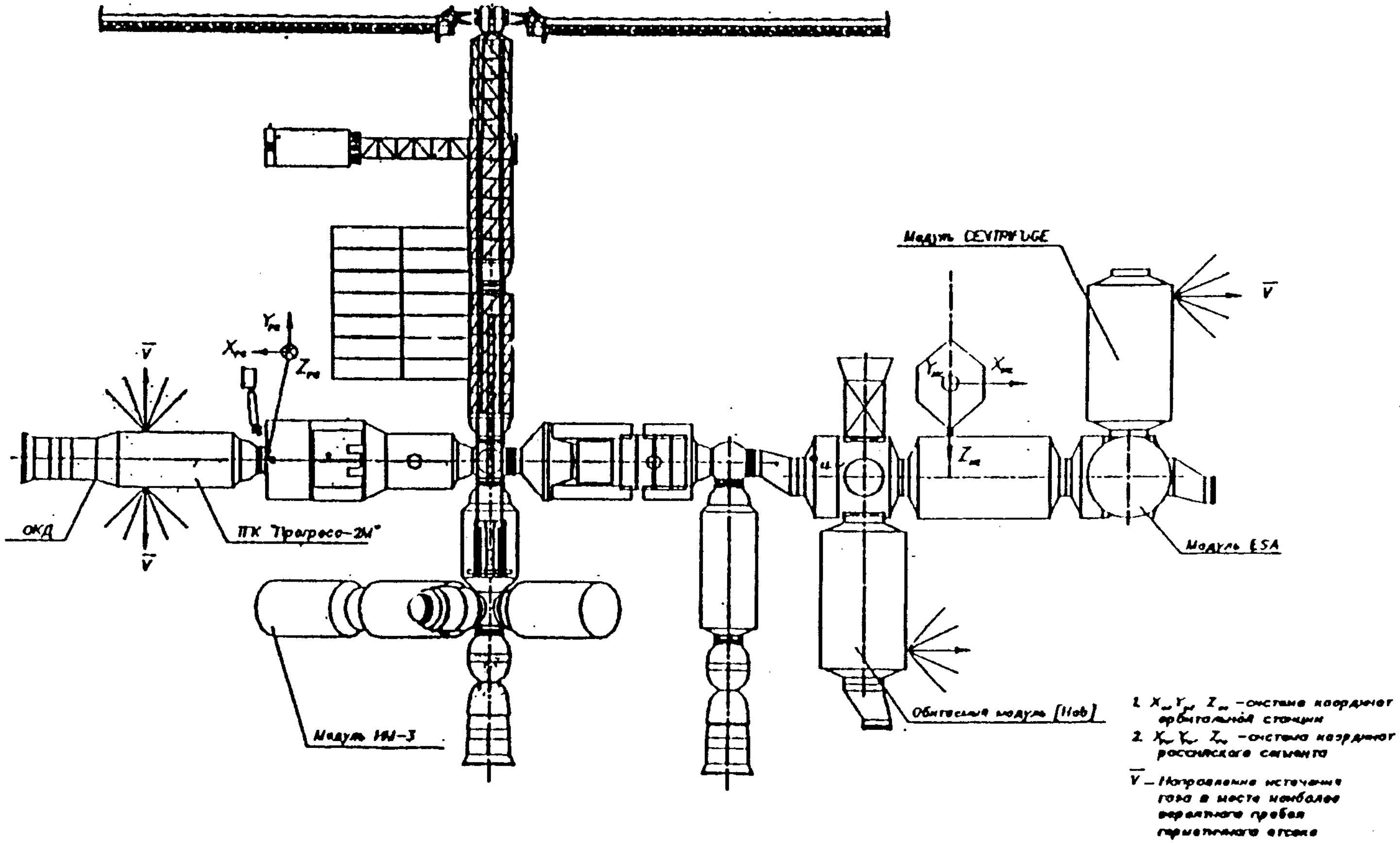


РИС.1

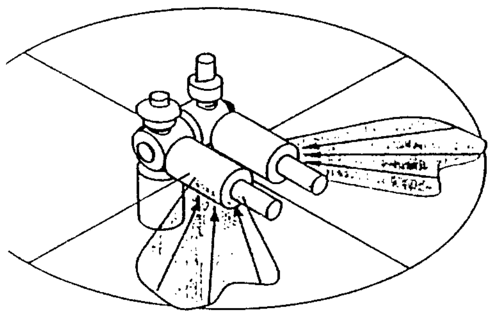
Critical Thrust Impact Locations
International Space Station Module Cluster

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Structures and Dynamics Laboratory

Structures Division
ED52 WILLIAMSEN
1996 NOV.

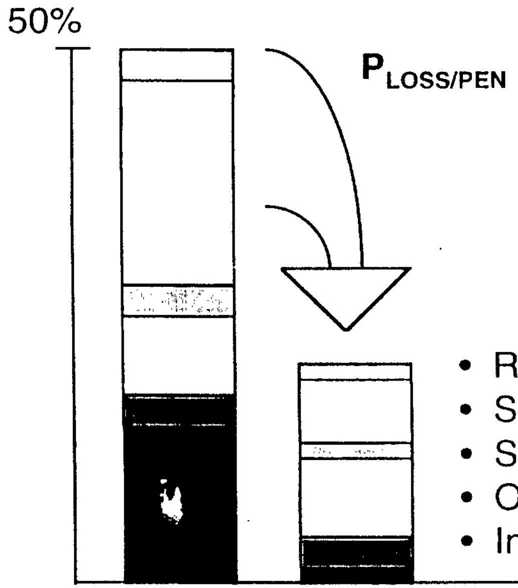
ED52 STRUCTURAL DEVELOPMENT BRANCH

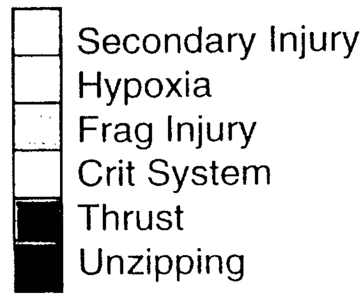
MINIMIZING SPACECRAFT OR CREW LOSS FOLLOWING PENETRATION



Environment Models

Fracture Analysis



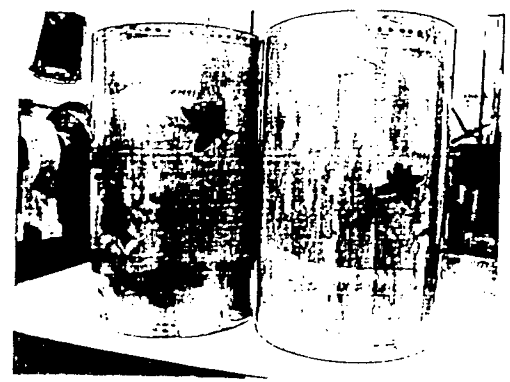


- Redesign Pressure Wall
- Selected Hatches Closed
- Safe Crew Sleep Position
- Oxygen Mask Placement
- Internal Spall Blanket

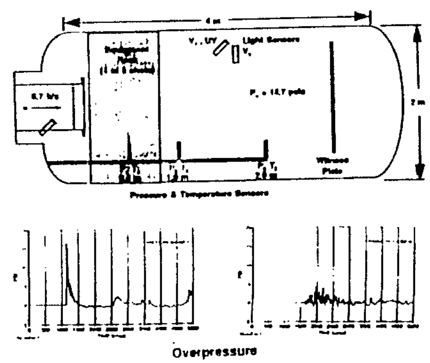
Baseline Improved Ops and Equipment

Manned Spacecraft and Crew Survivability (MSCSurv) Computer Simulation

- **Developed and Run at MSFC for:**
  - **Space Station Flight Operations (JSC)**
  - **Astronaut Office**
  - **ESA, NASDA, RSA**



Damage Prediction



Specialized Tests

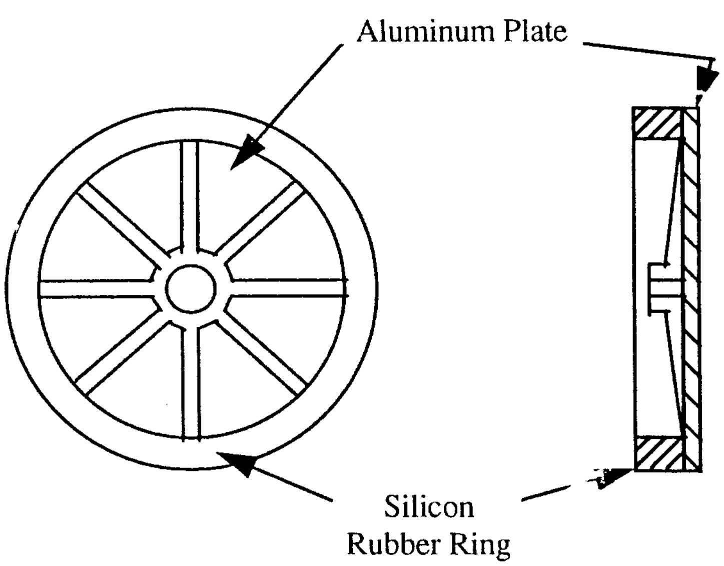
Marshall Space Flight Center
Structures and Dynamics Laboratory

International Space Station
Kit for External Repair of Module Impacts
from Meteoroids and Orbital Debris

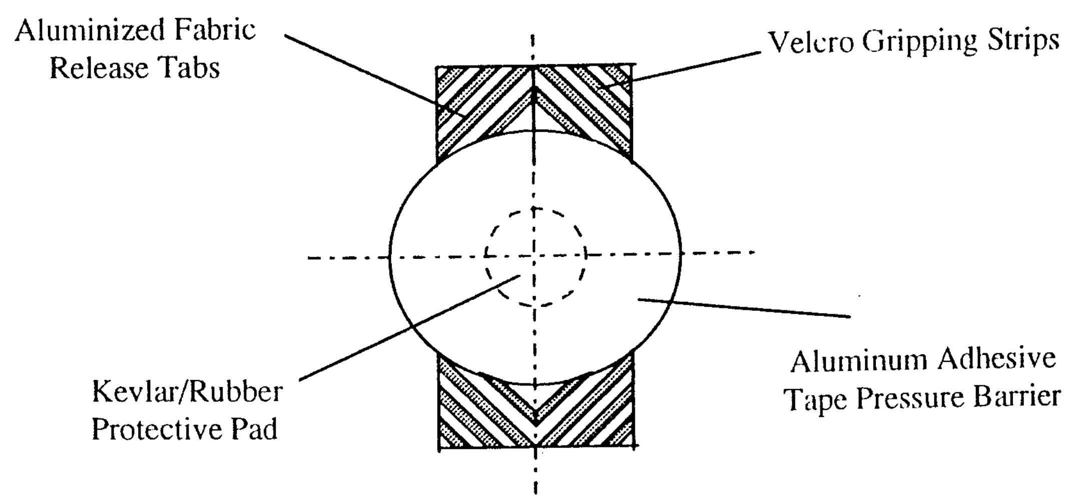
J. Williamsen
10 June 1997

Existing Internal Patch Types

Rigid Internal Repair Patch



Flexible Internal Repair Patch



Original KERMIt Patch Concept

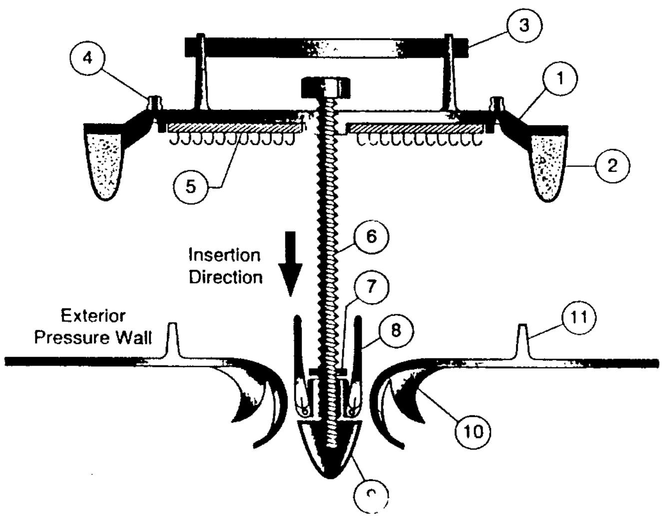


Figure 1. Patch probe inserted into hole.

Items

1. Patch Frame
2. Flexible Outer Seal
3. EVA Handle(s)
4. Adhesive Sealant zirc
5. Adhesive Interface Plate
6. Threaded Probe
7. Jam Nut
8. Spring-loaded Sprag Assembly (Collapsed Position)
9. Probe Tip
10. Damaged Pressure Wall with internal petals
11. Exterior structural feature (Grid) on Pressure Wall

1A-2810

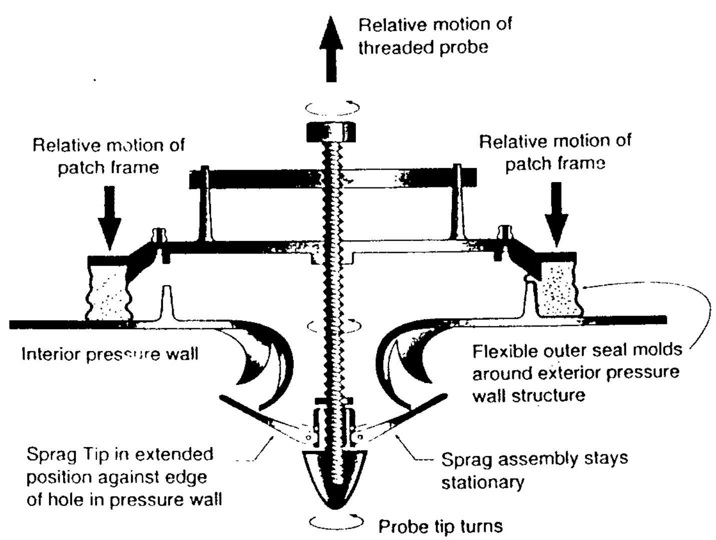


Figure 2. Patch lowered against exterior pressure wall.

1A-2811

International Space Station
Kit for External Repair of Module Impacts from Meteoroids and Orbital Debris

J. Williamsen
10 June 1997

Original KERMIt Patch Concept

External Adhesive Pressure W~" Patch

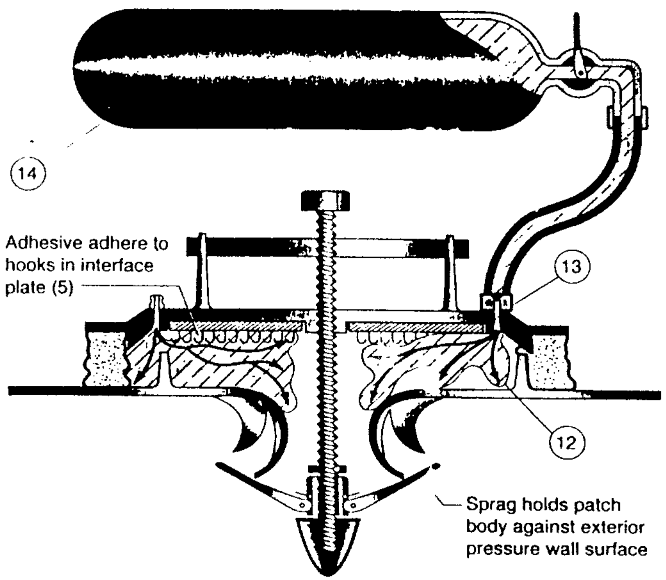


Figure 3. Patch body filled with adhesive sealant.

12. Liquid adhesive sealant
13. Flexible connection to patch zirc (4)
14. Adhesive sealant reservoir

1A-2820

Exter.al Adhesive Pressure Wall Patch

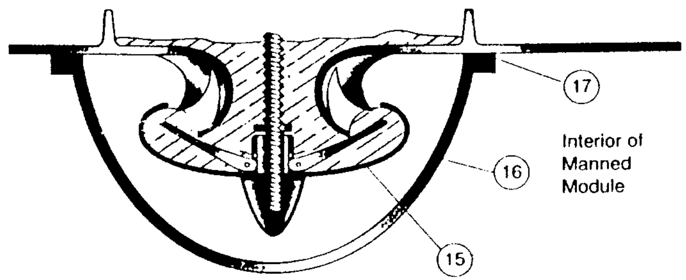


Figure 4. Optional internal seal components.

Items

15. Optional **flexible cap** over sprag assembly to contain liquid adhesive
16. **ınternal cover assembly** placed over sprag assembly following module re-pressurization to engure seal
17 ıternal cover seal (adhesive)

1A-2821

Ms. Teresa R. Anderson
Security Assistant
USAF - WL/DOY
Suite 1/WL/DOY
2130 Eighth Street
Wrigth-Patterson AFB, OH 45433
(513)255-3898 Fax (513)255-3717
ANDERSTR@wl.wpaf.af.mil

Mr. Timothy B. Armstrong
Veda, Inc.
Crystal Square Five, Suite 200
1755 Jefferson Davis Highway
Arlington, VA 22202
(703)413-4776 Fax (703)413-8031
tarmstrong.wcs5@veda.com

Mr. Dan B. Arnold
Airframe Manager
Boeing
P.O. Box 3707 MS 4C-42
Seattle, WA 98124-2207
(206)662-0762 Fax (206)662-0761
daniel.b.arnold@boeing.com

Mr. Dale B. Atkinson
Consultant
DBA
7703 Carrleigh Parkway
Springfield, VA 22152-1305
(703)451-3011 Fax (703)451-4278
dba@erols.com

Mr. Maurice C. Azar
Research Scientist
US Air Force
ATTN: AL/HRGO
3698 G Street
Wright-Patterson AFB, OH 45433
(937)255-3606 (513)255-3898 Fax (937)255-4250
ANDERSTR@wl.wpaf.af.mil

Dr. Robert E. Ball
Professor
Naval Post Graduate School
Dept. of Aero Astro
Code AA/BP
699 Dyer Road, Room 137
Monterey, CA 93943-5000
(408)656-2885 Fax (408)656-2313
ball@aa.nps.navy.mil

Mr. William G. Baron
Aerospace Engineer
Air Force Research Laboratory
JTCG/AS
WL/FIBAC, Bldg. 45, Suite 11
2130 Eighth St.
Wright-Patterson AFB, OH 45433-7552
(937)255-6630 Fax (937)656-7723
baronwg@wg.wpafb.af.mil

Mr. Michael P. Bartholomew
Chief, Air Team
Central Intelligence Agency
Weapons Defense Analysis Group
Washington, DC 20505
(703)874-0228 Fax (703)874-7268

Ms. Vivian Baylor
Program Manager
Oak Ridge National Laboratory
P.O. Box 2009, M/S-8206
Oak Ridge, TN 37831-8206
(423)241-5293 Fax (423)574-5169
baylorvm@orn.gov

Ms. Phyliss Bernier
2303 Sherwood Lane
Havre de Grace, MD 21078
(410)273-7722

Ms. Michele E. Bilowich
NDIA
Arlington Office
Suite 400
2111 Wilson Blvd
Arlington, VA 22201-3062
(703)522-1820 Fax (703)522-1885
mbilowich@adpansia.org

Ms Irene M. Bilyk
Engineer
Naval Air Warfare Center
Bldg 2187,Suite 2240
Patuxent River, MD 20670-1906
(301)342-9292 Fax (301)342-9305

Lt Paul A. Blue
United States Air Force
Wright Laboratory
Suite 21 WL/FIGC-3 Bldg 146
2210 Eighth Street
Wright-Patterson AFB, OH 45433-7531
(513)255-8683 Fax (513)476-4000
blue@falcon.flight.wpafb.af.mil

Mr. Gordon L. Boezer
Deputy Director/TIAC
Institute for Defense Analyses
STD/TIAC
1801 N. Beauregard Street
Alexandria, VA 22311-1733
(703)578-2776 Fax (703)931-7792
gboezer@ida.org

Mr. Larry G. Booth
Principal Systems Analyst
OSD Joint Data Support (Unisys
Suite 300
1225 Jefferson Davis Hwy
Arlington, VA 22202
(703)604-6394 Fax (703)604-6400
boothl@paesmtp.pae.osd.mil

Mr. Richard Bott
Engineer
Naval Air Warfare Center
Weapons Division
218 Peg St., Code 3183
China Lake, CA 93555
(760)939-6401
richard_bott@imdgw.chinalake.navy.mil

VADM Harold G. Bowen Jr.
USN (Ret)
Consultant
408 Crown View Drive
Alexandria, VA 22314-4804
(703)751-1472

Mr. William (Bill) C. Bowes
Sr VP
Hughes Aircraft Co.
Suite E1-A102
P.O. Box 902
El Segundo, CA 90245
(310)616-1547 Fax (310)616-1631
wcbowes@ccgate.hac.com

Col Ted Bowlds
USAF
SAF/AQP
Suite # 4E312
1060 Air Force Pentagon
Washington, DC 20330-1060
(703)697-0011 Fax (703)697-5653
bowldst@af.pentagon.mil

Mr. Lorenzo C. Bradley
ABDR Project Engineer
WL/FNS
Building 63
1901 Tenth Street
Wright-Patterson AFB, OH 45433-7605
(937)255-6179 Fax (937)255-2237

1Lt Mitchell M. Bradt
U S Air Force
Bldg. 63
1901 Tenth Street
WRIGHT PATTERSON AF, OH 45433-7605
(937)255-6179 Fax (937)255-2237

Mr. Douglas A. Brookbank
L.O. Product Manager
Pratt & Whitney
Large Military Engines
Suite 702-88
P.O. Box 209600
West Palm Beach, FL 33410-0960
(561)796-6165 Fax (561)796-7258

Mr. Leo D. Budd
Aerospace Engineer
Naval Air Warfare Center
Weapons Division
Code C2183
1 Administration Circle
China Lake, CA 93555-6001
(619)939-3328 Fax (619)939-2062

Mr. Roger D. Bullard
Technical Director
Northrop Grumman Corporation
3934/W3
1 Northrop Avenue
Hawthorne, CA 90250-3236
(310)332-2895 Fax (310)331-5028
roger_)bullard@ccmail.northgrum.com

Mr. Gerald J. Burblis
Sr. Survivability Analyst
Sikorsky Aircraft
Mail Stop S307A
6900 Main Street
Stratford, CT 06497-1378
(203)383-3489 Fax (203)386-5925
gburblis@sikorsky.com

Mr. Frank W. Burcham
Chief PRB
NASA Dryden Fligth
Research Center
PO Box 273
Edwards AFB, CA 93523-0273

Mr. Gary R. Burgner
Senior Test Consultant
ASI Systems International, Inc
825 North Downs
Ridgecrest, CA 93555
(619)375-1442 Fax (619)375-0230
GBURGNER@NDTI.NET

BG Charles M. Burke
USA
Deputy Commanding General
HQ USA VNC-DCG
US Army Warfighting Center
Ft. Rucker, AL 36362
(334)255-2612 Fax (334)255-3611
charles_burke@rucker-em4.army.mil

Lt Col Steven E. Cameron
OSD (A&T) DTSE&E
3110 Defense Pentagon
Washington, DC 20301-3110
(703)697-5806 Fax (703)614-7040
camerose@acq.osd.mil

Mr. Gerald M. Campbell
Sr. Tech Specialist
Northrop Grumman Corp
Suite U13
8900 E Washington Blvd
Pico Rivera, CA 90660
(562)948-6135 Fax (568)948-9927

Mr. John J. Campbell
Manager Advanced Projects
General Electric Aircraft Engi
6681 Old Station Drive
West Chester, OH 45069
(513)243-1269 Fax (513)243-1022

Mr. Nikolaos Caravasos
Manager, Military Tech.
Boeing
P.O. Box 16858
M/S P32-21
Philadelphia, PA 19142-0858
(215)522-2301

Mr. Huey D. Carden
Senior Research
NASA Langley Research Center
MS-495
12 W. Bush Road
Hampton, VA 23681-0001
(757)864-4151 Fax (757)684-8547

Mr. Daniel L. Carl
Electrical Engineer
UTRS, Inc.
Suite 208
950 N. Kings Highway
Cherry Hill, NJ 08034
(609)667-6770 Fax (609)667-7586
dlcutrs@erols.com

Mr. Warren B. Carroll
Associate Dept Manager
Battelle Hazardous Materials
Research Center
505 King Avenue
Columbus, OH 43201
(614)424-4743 Fax (614)424-4905
carroll@battelle.org

Capt Michael E. Clark
Reaseach Program Manager
US Air Force
AI/HRGO 2698 G Street
Wright-Patterson AFB, OH 45433
(937)255-2606 Fax (937)255-4250
mclark@alhrg.wpafb.af.mil

Mr. Gerald C. Cleaver
Technical Advisor
HQ AFOTEC/ST (USAF)
Directorate of Special Test
8500 Gibson Blvd SE
Kirtland AFB, NM 871175558
(505)846-9927 Fax (505)846-4285
cleaverg@afotec.af.mil

Mr. Britt M. Covington
USAF
Aerospace Structural Engineer
HQ AFSC/SEFE
9700 G Avenue, SE
Kirtland AFB, NM 87117-5670
(505)846-0990 Fax (505)846-6826
covingtb@smtps.saia.af.mil

Mr. Frank Crea
NAWCAD
Research & Engineering Group
Building 2187, Unit 5, Suite 1180
48110 Shaw Road
Patuxent River, MD 20670-1906
(301)342-8332 Fax (301)342-8367
crea_frank%pax5aemr.nawcad.navy.mil

Mr. Victor P. Crome
Director of Engineering
Litton Life Support
P O Box BX4508
2734 Hickory Grove Road
Davenport, IA 52804-4508
(319)383-6206 Fax (319)383-6107

Mr. Kevin R. Crosthwaite
Director S/V Information
Booz-Allen & Hamilton
Analysis Center (SURVIAC)
WL/FIVS/SURVIAC, Bldg. 45
2130 Eight Street, Suite 1
Wright-Patterson AFB, OH 45433-9673
(937)255-4840 Fax (937)255-9673
cresthwaite-kevin@bah,com

CAPT Michael G. Culjak
Chief, Test Plans & Reports Br
18th Flight Test Squadron/DOPM
606 Cruz Avenue
Hurlburt Field, FL 32544-5736
(850)884-1400 Fax (850)884-5675
culjakm@hqafsoc.hurlburt.af.mil

Mr. Bruce W. Cushing
Engineer
Boeing
P.O. Box 3707
Seattle, WA 98124
(206)662-0107

Mr. Walter J. Darling
Boeing North American, (SK97)
P.O. Box 3644
2600 Westminster Blvd.
Seal Beach, CA 90740-7644
(562)797-3964 Fax (562)797-1159
wdarling@netcom.com

Mr. George Robert Darwin
SAIC
Suite 2024151
1755 Jefferson Davis Hwy
Arlington, VA 22202
(703)413-3155 Fax (703)413-8059
darwinr@mail.etas.com

Mr. H. A. Davis II
IPT-CFA NAVAIR Chaff Countemea
NAWCAD
Unit 5, S. Engineering Center
48110 Shaw Rd.
Patuxent River, MD 20670-1906
(301)342-0084 Fax (301)342-0128
davisha%pax5a@mr.nawcad.navy.mil

Mr. R. Wayne Devereux
Technical Leader
Veda Inc.
22309 Exploration Dr.
Lexington Park, MD 20653
(301)863-4290 Fax (301)862-2530
Wdevereux.paxr@veda.com

Mr. Ronald M. Dexter
Sr. Survivability Engineer
Sikorsky Aircraft
6900 Main Street
PO Box 9729, M/S S317A
Stratford, CT 06497
(203)386-7922 Fax (203)386-5925
rdexter@sikorsky.com

Mr. Michael D. Dickerson
Consultant
Lockheed Martin
1930 Arrowhead Drive, N.E.
St. Petersburg, FL 33703-1904
(813)525-7848 Fax (813)525-7848
sgs@flanet.com

Cdr Stephen M. Dlugos
COMOPTEVFOR
7970 Diven Street
Norfolk, VA 23505
(757)444-5546 Fax (757)444-3820
dlugoss@cotf.navy.mil

Dr. Allen K. Dominek Ph.D., P.E.
Vice President
Analytic Designs, Inc
245 East Gay Street
Columbus, OH 43215
(614)224-9078 Fax (614)224-9080
akd@adinc.com

Mr. John J. Donnelly
Engineering Spec Sr.
Lockheed Martin Tectical Aircr
MZ 4263
P.O. Box 748
Ft. Worth, TX 76101-0748
(817)763-2033 Fax (817)777-7722
john.j.donnelly@lmco.com

Mr. William Dooley
System Planning Corporation
41797 Sheiloh Way
Hollywood, MD 20636
(301)866-1400 Fax (301)866-1402
bdooley@sysplan.com
(813)525-7848
sgs@flanet.com

Mr. Herbert W. Drake
Executive Vice President
4SI Systems International
Suite C
825 N. Downs
Pidgecrest, CA 93555
(760)375-1442 Fax (760)375-0230

CDR Wade D. Duym
USN (Ret.)
Manager, ASE Group
Battelle
505 King Ave.
Columbus, OH 43201
(614)424-4113 Fax (614)424-3776
duymw@battelle.org

Mr. Robert G. Eastin
Chief Scientific & Tech. Adv.
Federal Aviation Adm.
3960 Paramount Blvd.
Lakewood, CA 90712
(562)627-5205 Fax (562)627-5210
robert.eastin@taa.dot.gov

Maj Jon D. Edwards
U.S. Navy
DET, 182LTS
Hanger 109,
22474 James Road
Patuxent River, MD 20670
(301)342-7743
edwards_jon%pax93@mr.nawcad.navy.mil

Mr. Stephen L. English
Process Manager NBC-CS
US Army Joint Service Materie
5232 Fleming Rd.
Aberdeen Proving Gd., MD 21010-5423
(410)671-3264 Fax (410)671-2655
slenglis@codcom.apgcd.army.mil

Mr. Lawrence A. Eusanio
Research Staff
Institute for Defense Analyses
1801 N. Beauregard Stree
Alexandria, VA 22311-1733
(703)845-6922 Fax (703)845-6911
leusanio@IDA.org

RADM Marsha J. Evans
USN
Superintendent
Naval Postgraduate School
1 University
Circle Room M11
Monterey, CA 93943-5098
(408)656-2511 Fax (408)656-2337

Mr. Mike F. Falco
NAWCAD-PAX
Suite 1120-D1
Bldg 2187, Code 4.1.8
Patuxent River, MD 20670
(301)342-0143 Fax (301)342-8355

Mr. Curtis E. Fett
Project Engineer
U S Air Force
B-63
1901 Tenth Street
Wright-Patterson AFB, OH 85433-7605
(937)255-6179 Fax (937)255-2237

Mr. O. Douglas Fitch
Principal Engineer
The Boeing Company
9725 E. Marginal Way S.
Seattle, WA 98124-2207
(206)655-1910 Fax (206)662-2525
olgeir.fitch@boeing.com

Mr. Raymond R. Flores
Director, JTCG/AS
JTCG/AS Central Office
AIR 4.1.8 (JTCG/AS)
1725 Jefferson Davis Highway
Arlington, VA 22202-4102
(703)607-3500 Fax (703)325-0178
rflores@msis.dmso.mil

Mr. John E. Flynn
Manager Advanced Projects
GE Aircraft Engines
Military Engine Operations
H 345
1 Neumann Way
Cincinnati, OH 45215
(513)243-9227 Fax (513)243-5000
john.flynn@msx.ae.ge.com

Mr. James L. Fobes
FAA
807 Blue Teal
Absecon, NJ 08201
(609)485-4944 Fax (609)404-1012
fobes@admin.tc.faa.gov

Mr. James B. Foulk
President & CEO
The SURVICE Engineering Compan
Suite 103
1003 Old Philadelphia Road
Aberdeen, MD 21001-4011
(410)273-7722 Fax (301)272-7417
jimf@survice.com

Mr. Charles E. Frankenberger III
Live Fire Testing Eng.
Naval Air Warfare Center
Weapons Division
China Lake, CA 93555-6001

Mr. Guy S. Gardner
Associate Administrator R&C
Federal Aviation Administratio
Room 1000W
800 Indepoendence Ave, SW
Washington,, DC 20591
(513)243-9227
john.flynn@msx.ae.ge.com

Mr. Jeffrey Gavlinski
Sr. Project Engineer
US Army Materiel Systems Analy
AMXSY-AAM
Aberdeen Prvg Grd, MD 21005-5071
(410)278-6784

Mr. David J. Gerdeman
Wright Laboratory
2690 C Street
Wright-Patterson, OH 45433
(937)255-6185 Fax (937)656-7620
gerdemdj@wl.wpafb.af.mil

Capt Mark A. Gillespie
U S Air Force
Wright Laboratory
Bldg. 63
1901 Tenth Street
Wright-Patterson AFB, OH 45433-7605
(937)255-7125 Fax (937)255-2237

Mr. Frank C. Gillette
Director Chief Engineer
Pratt & Whitney
MS 726-06
P.O. Box 109600
West Palm Beach, FL 33410-9600
(561)796-2833 Fax (561)796-8790
gillette@pwfl.com

Mr. Kenneth S. Goff
Director, Survivability Div
NAVAIR HQ
Suite 1144
48110 Shaw Road Unit 5 Bldg 2187
Patuxent River, MD 20670-1906
(301)342-0142 Fax (301)342-8355
goffks.ntrprs@navair.navy.mil

RADM Robert H. Gormley
USN (Ret.)
President
The Oceanus Company
P.O. Box 7069
Menlo Park, CA 94026-7069
(650)854-8155 Fax (650)854-8753
oceanus@comuserve.com

Mr. Stephen J. Gould
Development Engineer
Pratt & Whitney
PO Box 109600
West Palm Beach, FL 33410-9600
(407)796-6409 Fax (407)796-7454
gouldste@pwfl.com

Dr. John R. Green
Senior Researcher
RAND
1700 Main Street
Santa Monica, CA 90407
(310)393-0411 Fax (310)451-7038

MG Paul L. Greenberg
USA (Ret.)
Vice President-Operations
NDIA
Suite 400
2111 Wilson Boulevard
Arlington, VA 22201-3061
(703)247-2559 Fax (703)522-1885
pgreenberg@adpa.org

MG Paul L. Greenberg
USA (Ret.)
Vice President-Operations
NDIA
Suite 400
2111 Wilson Boulevard
Arlington, VA 22201-3061
(703)247-2559 Fax (703)522-1885
pgreenberg@adpa.org

Mr. Hugh E. Griffis
Technical Specialist
US Air Force, ASC/XRA
1060 Stonehenge Dr.
Tipp City, OH 45371
(937)255-4358 Fax (937)656-7891
griffihe@xr.wpafb.af.mil

Mr. Robert Grove
Senior Analyst
Orlando Technology, Inc.
PO Box 855
Shalimar, FL 32579-0855
(904)651-5097 Fax (904)651-1481

Mr. John P. Haas
Senior Consultant
Booz-Allen & Hamilton Inc.
Suite 131
4141 Colonel Glenn Highway
Beavercreek, OH 45431
(937)431-2712 Fax (937)429-9795
haas-john@bah.com

Mr. Kenneth J. Hacker
Pgm Manager Aircraft Hardening
FAA William J. Hughes
Technical Center
AAR-520
Atlantic City Airport
Airport, NJ 08405
(609)485-4922 Fax (609)383-1973
hackerk@admin.tcfaa.gov

Mr. Dave Hall
Mathematician
Naval Air Warfare Center
Weapons Division
Code 418000D - MS/124D
1 Administration Circle
China Lake, CA 93555-6001
(619)939-3681 Fax (619)939-2062

Mr. G. R. Hammontree
Director IRCM Bus Dev
Northrop Grumman
Electronics & Systems Integrat
600 Hicks Rd.
Rolling Meadows, IL 60008-1098
(847)259-9600 Fax (847)590-3195

Mr. Glenn E. Harper
Sr Principal Tech Specialist
The Boeing Company
Advanced Systems & Technology
PO Box 516
Saint Louis, MO 63166-0516
(314)233-6459 Fax (314)232-4141
glenn.e.harper@boeing.com

Mr. David M. Harrah
Chief, Soldier Sys Control Brn
US Army Research Lab.
Human Research & Eng Dir.
Attn: AMSRL-HR-SC
Aberdeen Proving Gd., MD 21005
(410)278-5870 Fax (410)278-8828
dharrah@arl.army.mil

Maj Tony Hart
E C Test Mgr.
HQ AFOTEC/TFE
8500 Gibson Blvd.
Kirtland AFB, NM 87117
(505)846-8810 Fax (505)846-5203
hart@afotec.af.mil

Col. Gerald A. Hasen
USAF
Deputy Director AVD
Wright Laboratory (AFMC)
Flight Dynamics Directorate
WL/FI-I, Bldg 45, Suite 1
2130 Eighth St.
Wright-Patterson AFB, OH 45433-7542
(937)255-4012 Fax (937)255-3438
hasenga@wl.wpafb.af.mil

Mr. Edward N. Hathaway
Senior Associate
Booz Allen & Hamilton Inc.
8283 Greensgoro Drive
Mc Lean, VA 22102-3828
(703)902-5829 Fax (703)902-3374
hathaway_edward@bah.com

CDR Thomas A. Hejl
OSD
1800 Defense Pentagon
Washington, DC 20301-1800
(703)797-0521 Fax (703)698-7180
hejlt@paesmtp/pae.osd.mil

Mr. Ronald L. Henry
Mechanical Engineering Tech.
US Army Research Laboratory
Attn: AMSRL-SL-BL
Aberdeen Proving Grd, MD 21005-5068
(410)278-6304 Fax (410)278-6307
rlh@arl.mil

Mr. Stanley C. Herr
Senior Scientist
SAIC651-5097
4031 Colonel Glenn Hwy
Dayton, OH 45431-1673
(513)258-1170 Fax (513)253-9765
Stanley.C.Herr@cpmx.saic.com

Mr. Thomas E. Hess
Structures Div.
NAVIR
Bldg. 2187 Suite 2340
48110 Shaw Rd. Unit 5
Patuxent River, MD 20670-1906
(301)342-9363 Fax (301)342-9404

Ms. Janet S. Hodges
Manager, Western Regional Offi
Defense Technical Information
Suite#906
222 N. Sepulveda Blvd.
El Segundo, CA 90245
(310)335-4170 Fax (310)335-3663
jhodges@dtic.mil

Mr. Andre J. Holten
Principal Staff Member
BDM
1801 Randolph Road S.E.
Albuquerque, NM 87106
(505)848-5328 Fax (505)848-5248
aholten@bdm.com

Ms Martha L. Hoppus
Program Analyst
Naval Air Warfare Center
1 Administration Cir
China Lake, CA 93555
(760)446-3370 Fax (760)927-1265

Mr. Tex W. Hoppus
Head RF Guidance Branch
Naval Air Warfare Center
Code 472200D
China Lake, CA 93555
(760)939-3080 Fax (760)939-3075
tex-hoppys@mingw.chinalake.navy.mil

Mr. Richard A. Horton
Head, Survivability Division
DoD
Code 418000D
1 Administration Circle
China Lake, CA 93555-6001
(619)939-3681 Fax (619)939-2062

BrigGen Michael A. Hough
USMC
Joint Strike Fighter
6603-H Thackwell Way
Alexandria, VA 22315
(703)602-7640 Fax (703)602-7649
hough@jast.mil

Ms. Diana S. Howdyshell
Security Asst.
US Air Force
2130 Eighth St. , Stei
WLIDOY
WPAFB, OH 45433-7542
(513)255-3898 Fax (513)476-7074

LTC Jesse A. Huerta
US Air Force
SAF/AQPT
Washington, DC 20330-1060
(703)695-0328

Mr. Joseph P. Hylan
NDIA
Suite 400
2111 Wilson Blvd.
Arlington, VA 22201
(703)522-1820 Fax (703)522-1885

Mr. William W. Hyland Jr.
Systems Engineer
ORC, Inc.
Suite 1450
1225 Jefferson Davis Hwy.
Arlington, VA 22202
(703)414-5453 Fax (703)414-5469
hylandw@orc.com

Mr. James W. Hypes
Sr. Aircraft Analyst
Central Intelligence Agency
Washington, DC 20505-0001

Mr. John R. Italiane
Director, Safety Systems
Primex Aerospace Company
11441 Willows Road
Redmond, WA 98052
(425)835-5002 Fax (425)802-5744
jri@red.primextech.com

1 Lt Dennis J. Jackson II
Test Aviation
US Air Force
1901 Tenth Street
WL/fivsm Bldg 63
Wright Patterson AFB, OH 45433-7605
(513)255-6052

Mr. Francis G. Jasinskas
Manager, Market Development
General Electric Aircraft Engi
Suite 806
5933 W. Century Boulevard
Los Angeles, CA 90045
(310)642-5256 Fax (310)642-5250
frank.jasinskas.ae.ge.com

Mr. Jack R. Johnson
Lead, V-22 IPT Team
Bell Helicopter Textron
PO Box 48265
Fort Worth, TX 76101-0482
(817)280-3506 Fax (817)280-8304
jackj@computek.net

RADM Mike Johnson
USN
Dir, Aviation Plns & Reqs
OPNAV
Branch N880
2000 Navy Pentagon
Washington, DC 20350-2000
(703)697-1446 Fax (703)614-7047
johnson.michael@hq.navy.mil

Mr. Joseph P. Jolley
General Engineer
JTCG/AS Central Office
Suite 1003, Crystal Square #2
1725 Jefferson Davis Highway
Arlington, VA 22202
(703)280-5167 Fax (703)280-5169
jolley2@tecnetl.jcte.jcs.mil

Mr. Chantal Joubert
Manager, Aircraft Protection
The Boeing Company
Advanced Aircraft Program
M/C: 71-23
2401 E. Wardlow Road
Long Beach, CA 90807-5309
(310)593-7950 Fax (310)982-0815

Mr. David M. Kane
Sr. Technical Specialist
Northrop Grumman
One Hornet Way 9B74/WB
El Segundo, CA 90245
(310)332-9623 Fax (310)332-9160
dkane@world.northgrum.com

Ms Gina M. ´ ıuppi
Resoures Spᴗcialist
NAWCWPNS
Bldg 3119 code 418300d
China lake, (\ 93555
(760)939-6208 Fax (760)939-6213

Mr Edward L. Kennedy
Systems Engineer
Department of Defense
Office of Test & Eval Director
Attn: OTD (Army Branch)
White Sands, NM 88002-5519
(505)678-7239 Fax (505)678-7288

Mr. Kelly J. Kennedy
Systems Integration Engineer
ASC/XRA
Suite #10
2275 D Street
Wright Patterson AFB, OH 45433
(937)255-4358 Fax (937)656-7891
KENNEDKT@XR.WPAFB.AF.MIL

Mr. Timothy J. Kinne
Manager, Spec Mil Prod Eng
GE Aircraft Engines
1 Neumann Way, G115
Cincinnati, OH 45215
(513)243-5308 Fax (513)243-1022
tim.kinne@ae.ge.com (310)332-9623
dkane@world.northgrum.com

Mr. Odious O. Knight
Director, Systems Integration
United States Army Special Ope
Bldg E29M Desertstorm Road
Ft. Bragg, NC 28307
(910)432-5335 Fax (910)432-1661
knighto@soc.mil

Col. Karl M. Kochel
U.S. AirForce
Deputy for Air Force EW Prgms.
OUSD (A&T)/S&TS/EW
3090 Pentagon
Washington, DC 20252
(703)695-1208 Fax (703)614-8811
Kocholkm@acq.osd.mil

Mr. James C. Kolding
Senior Analyst
Boeing Company
MS M531-C240
5000 E. McDowell Road
Mesa, AZ 85215
(602)891-4097 Fax (602)891-5280
james.c.kolding@boeing.com

Mr. Mathias L. Kolleck
Manager Advanced Tech.
Booz, Allen & Hamilton Inc.
4141 Colonel Glenn Highway
Suite 131
Beaver Creek, OH 45431-1662
(513)429-9509 Fax (513)429-9795
kolleck@bab.com

Ms. Theresa Kopa
WL/DOY, Building 45
2130 Eighth Street, Suite 1
Wrigth-Patterson AFB, OH 45433-7542
(937)255-5113 Fax (937)255-3717

Mr Michael Kouvarakos
Aerospace Engineer
NAWCAD
Bldg. 2187, Unit 5
48110 Shaw Road
Patuxent River, MD 20670-1906
(301)342-8318 ɹx (301)342-8355
kouvarakosm.ntrprs@navair.navy.mil

Capt Steven A. Kunkle
Staff Specialist
OUSD(A&T)/S&TS-Air Warfare
Room 3E1081
3090 Pentagon
Washington, DC 20304-3090
(703)695-3015 Fax (703)614-7060
kunclesa@acq.osd.mil

Mr. Alex G. Kurtz
Aero Engineer
US Air Force
WL/FIVS-1, Building 63
1901 Tenth Street
Wright Patterson AFB, OH 45433-7605
(513)255-6179 Fax (513)255-2237

Mr. Leo E. Labaj
Program Manager
Oak Ridge National Lab
P.O. Box 2009, M/S-8206
Oak Ridge, TN 37831
(423)241-3295 Fax (423)574-5169
labajle@ornl.gov

Mr. Ralph W. Lauzze II
Director, JLF Test
US Air Force
ATTN: WL/FIV
1901 10th Street
Wright-Patterson AFB, OH 45433-7605
(513)255-6823 Fax (513)255-2237
lauzzerw@wl.wpafb.af.mil

Mr. Dean I. Lawry
Electronic Engineer
US Air Force Research Laborato
AFRL/DEOB
3550 Aberdeen Ave., S.E.
Kirtland AFB, NM 87117-5776
(505)853-3392 Fax (505)846-5776
lawry@plk.af.mil

Mr. Richard R. Ledesma
Deputy Director
Deputy Director
Rm 3D18080
3110 Defense Pentagon
Washington, DC 20301-3110
(703)695-4421 Fax (703)614-7040
ledesmrr@acq.osd.mil

Mr. Warren M. Lee
Technical Advisor
AFOTEC
Modeling & Analysis Division
8500 Gibson Boulevard SE
Kirtland AFB, NM 87117-5558
(505)846-1359 Fax (505)846-5145
leew@afotec.fl.mil

Mr. David R. Lincks
Engineer
Boeing Info Space & Defense Sy
P.O. Box 3707
MS 4X-57
Seattle, WA 98124-2207
(425)393-1974 Fax (425)393-5848
david.r.lincks@psboeing.com

Mr. Arthur W. Linden
VP, Program Director
Boeing Sikorsky
Commanche Program Office
International Plaza II
Suite 645, MS P31-20
Philadelphia, PA 19113
(610)362-1002 Fax (610)362-1025

Mr. Anthony S. Lizza
Aerospace Engineer
USAF-ASC/FB
Suite 16
2275 D Street
Wrigth-Patterson AFB, OH 45433-7233
(937)255-0935 Fax (937)656-4102
lizzaas@lawpafb.af.mil

Maj Richard P. Lockwood
USAF
AF Liaison
JTCG/AS Central Office
Crystal Square #2, Suite 1003
1725 Jefferson Davis Highway
Arlington, VA 22202-4102
(703)607-35[illegible] Fax (703)602-5387
rltcgas@tecnet1.jcte.jcs.mil

Mr. Alex Loewenthal
LM Skunk Works
1011 Lockheed Way
Palmdale, CA 93599-2514
(805)572-7014 Fax (805)572-4561
alex.loewenthal@lmco.com

Mr. Daniel W. Lotz
Senior Analyst
OD PA&E/IMAG (GRCI)
Suite #300
1225 Jefferson Davis Highway
Arlington, VA 22202
(703)604-6349 Fax (703)604-6400

Mr. Carl V. Lyday
Director
Univ. of Denver Research Inst
BW 120
2050 E. Iliff Ave.
Denver, CO 80208
(303)871-4226 Fax (303)871-2716
clyday@du.edu

COL Robert Lyons Jr.
Joint Strike Fighter
Suite 307
1745 Jefferson Davis Highway
Arlington, VA 22202
(703)602-73[illegible] Fax (703)602-0593
rlyons@jast.[illegible]

Col. Robert P. Lyons Jr.
USAF
Joint Strike Fighter Office
JSF X-32
Arlington, VA 22202

Mr. Thomas P. Mahan Jr.
Manager, Survivability
Lockheed Martin Skunk Works
1011 Lockheed Way
Palmdale, CA 93599-7242
(805)572-5525 Fax (805)572-2343
tmahan@ladc.rockheed.car

Mr. Thomas J. Mallets Sr.
Logistics Specialist
USAF/AF Materiel Command
Suite 1
4170 Hebble Creek Rd.
Wright Patterson AFB, OH 45433-5653
(513)257-7899 Fax (513)476-1230

Maj Gen Gregory S. Martin
USAF
Director of Operational Req
HQ USAF/XOR
1480 Air Force Pentagon
Washington, DC 20330-1480
(703)695-3018 Fax (703)614-4011
marting@af.pentagon.mil

Mr. Roger I. Martinez
Electronics Engineer
NAWCAD-Pax River
Suite 1120-D2
Bldg 2187
Patuxent River, MD 20670
(301)342-0164 Fax (301)342-8355
martinez-roger%paxta@mr.nawcad.navy.mil

Mr. Jack F. McGuire
Director Structures Eng.
Boeing Commercial Airplane Gro
MS 67-UT
535 Garden Ave., N.
Renton, WA 98055
(425)234-9991 Fax (425)234-9941

LTC Joseph W. McVeigh
USA
TSM Command
Ft. Rucker, AL 36362
(324)255-2160

Mr. Michael H. Merrill
Sr Analyst
Raytheon TI Systems
Unit #907
17490 Meandering Way
Dallas, TX 75252
(972)575-4841 Fax (972)575-6009
mike.merrill@u.com

Mr. Robert J. Meyer
Operations Research Analyst
Naval Air Warfare Center
Code 418200D (124D)
1 Administration Circle
China Lake, CA 93555-6100
(760)927-1279 Fax (760)939-2062
bob_meyer@imdgw.chinalake.navy.mil

Mr. Michael Meyers
Sr. Principal Tech. Specialist
The Boeing Company
MC S270-1227
PO Box 516
Saint Louis, MO 63132-0516
(314)234-8913 Fax (314)233-0303
michael.meyers@boeing.com

Mr. William A. Moore
Program Director
Northrop Grumman Corp.
F-18 New Business, FG001
MASD, One Hornet Way
El Segundo, CA 90245-2804
(310)332-1456 Fax (310)331-1052
william_moore@ccmail.northgrumm.com

Dr. L. Kent Morrison
Chief, Aviation Branch
US Army Research Lab
AMSRL-SL-EV-, Bldg 1624
WSMR, NM 88002-5513
(505)678-6165 Fax (505)678-8720
kmorriso@hermes.arl.mil

Dr. N. Albert Moussa
Technical Director
BlazeTech Corporation
Suite 19
21 Erie Street
Cambridge, MA 02139-4260
(617)661-0700 Fax (617)661-9242
amoussa@blazetech.com

Mr. Donald W. Mowrer
Vice President
The SURVICE Engineering Compan
Suite 103
1003 Old Philadelphia Rd.
Aberdeen, MD 21001-4011
(410)273-7722 Fax (410)272-7417

Dr. Paul R. Muessig
Deputy Project Manager
Naval Air Warfare Center
Weapons Division
Code C21806
1 Administration Circle
China Lake, CA 93555-6001
(619)939-3680 Fax (619)939-2062

LCDR John F. Murphy
Safety Officer /P-3 NATOPS
Compat Wings PAC Evaluator
Nas Barbers PT, HI 96862
(808)684-0358 Fax (808)684-8257

MAJ Michael L. Murphy
USMC
MV-22 Operational Tes Dir.
HMX-1
NAWC
Patuxent River, MD 99999
(301)342-7943

Mr. Ronald Mutzelburg
Deputy Director, Air Warfare
OUSDA(A&T)/S&TS-AW
The Pentagon, Room 3E1081
3090 Defense Pentagon
Washington, DC 20301-3090
(703)695-0525 Fax (703)614-7060
mutzelre@acq.osd.mil

Maj Mark A. Naumann
USAF
Program Manager
HQ AMC/XPRS
402 Scott Dr. Unit 3L3
Scott AFB, IL 62225 5307
(618)256-3908 Fax (617)256-5001
naumannm@hqamc.safb.af.mil

Mr. John P. O'Brien
Director, EW Programs
Raytheon Company
Suite 1500
1215 Jefferson Davis Highway
Arlington, VA 22202-4302
(703)416-5809 Fax (703)416-5959
john_p_obrien@ccmail.eo.ray.com

Mr. James F. O'Bryon
Deputy Director
Office of the Secretary of Def
Operational T&E (Live Fire Tes
Room 1C730
1700 Defense Pentagon
Washington, DC 20301-1700
(703)614-5408 Fax (703)614-3992
jobryon@dote.osd.mil

Mr. Charles R. O'Roarke
Crew Systems Engineer
NAS
Suite 2240
48110 Shaw Rd.
Patuxent River, MD 20670
(301)342-9211 Fax (301)342-9299

Mr. Stephen D. Owens
Engr. Specialist Sr.
Lockheed Martin Tactical Aircr
P.O. Box 748
Ft. Worth, TX 76101
(817)777-2142 Fax (817)777-4254
sdowens@lmtas.lmco.com

Mr. John E. Passfeld
Electrical Engineer
NAWC
BLDG 2187, Suite 1120-A3 Unit #5
48110 Shaw Road
Patuxent River, MD 20670
(301)342-0150 Fax (301)342-8355
passfeldjohn%pax5a@mr.nawcad.navy.mil

Mr. John M. Paterson
Senior Engineer
Northrup Grumman
MS: 6J50/UB
8900 E. Washington Boulevard
Pico Rivera, CA 90660
(310)948-0689

Mr. John M. Perdzock
Electronic Engineer
US Air Force
WL/F/GS
Wright-Patterson AFB, OH 45433
(937)255-3777

Mr. Jack Pledger
Noirthrop Grumman
1633 Eleventh Fairway Drive
Belleville, IL 62220
(618)233-7781
jpledger@northrop.geis.com
(817)777-2142
sdowens@lmtas.lmco.com

Mr. Roger B. Podob
Naval Air Warfare Center
Research & Engineering Group
47110 Liljencrantz Road
Patuxent River, MD 20670-1545

Mr. Paul A. Polski
Director, Aviation SR&D
FAA William J. Hughes
Technical Center
Bldg 315I
Atlantic City
Airport, NJ 08405-0001
(609)484-4958

Col Mike F. Poore
USAF
Joint Strike Fighter
Suite 307
1745 Jefferson Davis Hwy
Arlington, VA 22202
(703)602-7390 Fax (703)602-7649
pooref@jast.mil

COL Fred B. Raines
USA (Ret.)
Director, Technical Services
NDIA
Arlington Office
Suite 400
2101 Wilson Blvd
Arlington, VA 22201-3062
(703)522-1820 Fax (703)522-1885
fraines@adpa.org

Mr. Thomas D. Rains
Dir. Military Programs
The Boeing Company
M510A396
5000 E. McDowell
Mesa, AZ 85215-9707
(602)891-5051 Fax (602)891-5509
thomas.d.rains@boeing.com

Mr. Peter T. Reiss
Chairman Security Committee
Intl Federation of Air Line Pi
Associations
421 Roxgury Road
Hudson, NY 12534-9732
(518)672-7520 Fax (518) 672-7342

Mrs. Lorinda M. Retrossa
Mechanical Engineer Tech
US Army Aberdeen Test Center
Attn: STEAC-LI-MS
Aberdeen Provg Grd, MD 21005-5059
(410)278-8844 Fax (410)278-6944

Major Ronald F. Richard
USAF
Chief, Strategic & Doctrine
Air Force Special Operation Co
38 Lakeview Drive
Maryesther, FL 32569
(850)581-1089 Fax (850)884-4765
richarrf@hqafsoc.hurlburt.af.mil

Col. Roland G Richardella
USMC
DASN (Air Programs)
Suite#5E715
1000 Navy Pentagon
Washington, DC 20350-1000
(703)614-7794 Fax (703)614-7874
richardella.rich@hq.navy.mil

Mr. William A. Ricks
Aerospace Engineer
NAVAIR
48348 Long Lane
Lexington Park, MD 20653
(301)342-8329
rickswa.ntrpes@navair.navy.mil

Mr. Rimi O. Rivera
Chemical Engineer
NAWCAD
Code 4.3.4.3. Build 2188 Unit 5
48066 Shaw Road
Patuxent River, MD 20670-1908
(301)342-8036 Fax (301)342-8077
rimi%PAX5@mr.nawcad.navy.mil

Ms. Joan M. Ross
Intelligence Research Spec.
U S Air Force
8500 Gibson Blvd SE
Kirtland AFB, NM 87117-5558

Capt Martin L. Rothrock
U S Air Force
653 Carol Ann Drive
O'Fallon, IL 62269
(618)256-5280 Fax (618)256-8645

Mr. Timothy B. Russell
Electronic Engineer
NAIC/TANV
4180 Watson Way
WPAFB, OH 45433
(937)257-3255 Fax (937)656-1295

Mr. Constantine P. Sarkos
Manager, Fire Safety Section
FAA William J. Hughes
Technical Center
Building 3151
Atlantic City
Airport, NJ 08405-0001

Mr. Gus Sarkos
Manager of Fire Safety
FAA WM J.Hughes Technical Cntr
AAR422, Bldg 204
Atlantic City Air, NJ 08405
(609)485-5620 Fax (609)485-5785

MAJ James B. Schafer
Test Director
United States Marine Corps
2101 Ronell Road
Quantico, VA 22134
(703)784-2923 Fax (703)784-2224

Mr. Marvin B. Schaffer
Consultant
RAND
1700 Main Street
Santa Monica, CA 90401-3208
(310)393-0411 Fax 310-393-4818
marv@rand.org

Mr. William Scheffler
Aviation Advisor Marine Corps
Marine Corp. Warfighting LAB
Suite 201
2042 Broadway
Quantico, VA 22046
(703)784-1088 Fax (703)784-1378
schefflernw@quantico.usmc.mil

Mr. Raymond M. Schillinger
Aerospace Engineer
FAA Technical Center
AAR-520
Atlantic International Airport
Atlantic City, NJ 08405-0001
(609)485-4927 Fax (609)383-1973
schillir@admin.tc.faa.gov

CW5 Karl H. Schmidt
USA
United States Army
P.O. Drawer 2
Ft. Eustis, VA 23604
(757)820-1000 Fax (757)820-1124

Dr. Mark W. Schraad
Los Alamos National Laboratory
Grow T-3, Mail Stop B216
Los Alamos, NM 87545
(505)665-3946 Fax (505)665-5926
schraad@lanl.gov

Mr. Eric R. Schwartz
Sr. SCPA
The Boeing Company
MC 1003450
PO Box 516
St. Louis, MO 63166-0516
(314)232-4991

Dr. Harshad K. Shah
Electronics Engineer
Department of the Navy
Suite 1140 B-2
Bldg 2187 48110 Shaw Road, Unit 5
Patuxent River, MD 20670-1906
(301)342-0151 Fax (301)342-8355
shah_harshad%pax5a@mr.nawcad.navy.mil

Mr Harry T. Shamansky
President
Analytic Design Incorporated
245 East Gay Street
Columbus, OH 43215-3210
(614)224-9078 Fax (614)224-9080
hts@adinc.com

Mr. Richard E. Sheffield
Director, ADP&CT
Lockheed Martin Corp.
Suite 300, Crystal Square 2
1725 Jefferson Davis Highway
Arlington, VA 22202-4127
(703)413-5740 Fax (703)413-5722
butch.sheffield@lmco.com

Mr. James M. Shipman
Vulnerability Reduction Mgr.
Pratt & Whitney (GESP)
Government Engines
MS 712-43
PO Box 109600
West Palm Beach, FL 33410-9600
(561)796-5996 Fax (561)796-9088
shipman@pwfl.com

Mr. Kent F. Smith
Aerospace Engineer
US Army AMCOM
Attn: AMSAM-AR-T-V
Fort Eustis, VA 23604-5577
(757)878-5875 Fax (757)878-2543
ksmith@eustis-aatds1.army.mil

Mr. Lloyd H. Smith Ph.D.
Director of Business Dev.
ASI Systems International
825 N. Downs
Ridgecrest, CA 93555
(760)375-1442 Fax (760)375-0230

Mr. Ralph J. Speelman
Aerospace Engineer
US Air Force
WL/ELVS
Wright-Patterson AFB, OH 45433
(937)255-6823 Fax (937)255-2237

Mr. Larry T. Stephens
F-22 Vulnerability/Live Fire
Lockheed Martin Aeronautical S
1322 Amberwood Drive
Woodstock, GA 30189
(770)494-9117 Fax (770)494-9142
lt.stephens@mar.lmco.com

Mr. James E. Steve Stephenson
Mtls Engineer
Naval Air Systems
8110 Sleepy View Lane
Springfield, VA 22153
(703)342-8306
(757)878-5875
ksmith@eustis-aatds1.army.mil

Mr. William M. Stewart
Engineering Specialist
Lockheed Martin Tactical Aircr
P.O. Box 748 , MZ4263
Fort Worth, TX 76101
(817)763-1909 Fax (817)777-7722
w-mark.stewart@LMCD.com

Mr. Ray E. Stratton
Manager
Lockheed Martin Corporation
Suite 810
1 N. Dale Mabry
Tampa, FL 33609-2757
(813)871-5450 Fax (813)873-8082
ray.stratton@lmco.com

Mr. Robert G. Struth
U.S. Navy
Manager, Systems Engineering J
The Boeing Co.
27173 SE 26th Place
Issaquah, WA 98029
(206)544-6104 Fax (206)662-2525

Mr. R. Daniel Sullivan
HQ USAF/XORFS
1480 AirForce Pentagon
Washington, DC 20330-1480
(703)696-4999 Fax (703)696-6984
sullivanr@af.pentagon.mil

Ms. Kathleen L. Tarquini
Operations Research Analyst
US Army Evaluation Analysis Ce
ATTN: CSTE-EAC
Aberdeen Proving Gr., MD 21005-3013
(410)278-5046 Fax (410)278-2287
tarq@arl.mil

Mr. Hase W. Taylor
Systems Analyst
Unisys
Suite 300
1225 Jefferson Davis Hwy
Arlington, VA 22202
(703)604-6349 Fax (703)604-6400
taylorh@paesntp.pae.osd.mil

CW3 Darrell K. Tolle
US Army
502 K Ave.
Ft. Rucker, AL 36362
(334)255-1477 Fax (334)255-1444
darrell_tolle@rucker-emh4.army.mil

Mr. Thomas J. Toner
Sys Integ Manager
UTC-Sikorsky Aircraft Corp.
5328A4
6900 Main St.
Stratford, CT 06601
(203)386-5842 Fax (203)386-7941
ttoner@zoomit.sikorsky.com

Maj John N. Torres
USMC
Operational Test Director
United States Marine Corps
Unit ID Navacad
Patuxent River, MD 20670-1624
(301)757-0221 Fax (301)757-0076
torres-john.pax98@mr.nawcad

Mr. Thomas J. Trigg
Sr. Project Engineer
The Boeing Company
P O Box 516
St. Louis, MO 63166
(314)232-0161 Fax (314)233-8005

1Lt James R. Tucker
U S Air Force
Bldg 63
1901 Tenth Street
Wright-Patterson AFB, OH 45433-7605
(937)255-7125 Fax (937)255-2237
tuckerjr@b945mail.wpafb.af.mil

Mr. John M. Vice
Consultant
Skyward, Ltd.
3468 Fairwood Dr.
Beaver Creek, OH 45432-2362
(937)427-4261 Fax (937)431-1580
110310.174@compuserv.com

Mr. E. Michael Vogel
Electronic Engineer
US Army Research Laboratory
Attn: AMSRL-[illegible]L-B
Aberdeen Provg Grd, MD 21005-5068
(410)278-5855 Fax (410)278-9399
mvogel@arl.mil

Mr. Donald W. Voyls
Program Manager
US Air Force
WL/FIVS
1901 10th Street BLDG. 63
Wright Patterson AFB, OH 45433-7605
(937)255-6179 Fax (937)397-2552

Mr. Sam S. Waggener
Physicist
Naval Surface Warfare Center
G-22
17320 Dahlgren Road
Dahlgren, VA 22448-5150
(540)653-4263 Fax (540)653-4662
swaggen@nswc.navy.mil

Mr. William E. Waldron
General Engineer
Navy/NAVAIR
6033 Sweet Oak Ct.
Springfield, VA 22152
(703)913-1055 Fax (703)604-2042
waldronwe@navair.navy.mil
(937)427-4261
110310.174@compuserv.com

Mr. Kenneth E. Wall
Research Staff
Institute for Defense Analyses
1801 North Beauregard Street
Alexandria, VA 22311
(703)845-2219 Fax (703)854-6977
rwall@ida.org

Mr. Jerry Wallick
Member, Research Staff
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311-1772
(703)845-2353 Fax (703)845-6977
jwallick@ida.org

Mr. Allan J. Wearner
JFL Navy DTD
Naval Air Warfare Center
Weapons Division
Code C21803
1 Administration Circle
China Lake, CA 93555-6001
(619)927-1249 Fax (619)939-2062

Mr. Michael R. Weisenbach
LFT/Vulnerability Engineer
U.S. Air Force
ASC/YFE
2130 Fifth Street
Wright Patterson AFB, OH 45433
(513)255-2353 Fax (937)255-6956
weisenbachmr@asc-yf.wpafb.af.mil

LTC Stanley E. Wells
U.S. Marine Cor
MCCDC
3300 Russell Road
Quantico, VA 22202
(703)784-23[illegible] Fax (703)784-2532
wellss@quantco.usmc.mil

Capt Kevin O. Westley
Flight Test Analyst
DET 1, 31TES
8500 Gibson Blvd.
Kirtland AFB, NM 87123
(505)846-4468 Fax (505)846-1940
westleyk@afstec.af.mil

Dr. Stephen R. Whitehouse Ph.D.
Senior Engineer
Applied Research Associates, I
Suite A-220
4300 San Mateo Blvd. NE
Albuquerque, NM 87110
(505)883-3636 Fax (505)883-3673

Mr. Earl E. Wilhelm
Senior Principal Engineer
Boeing Defense & Space Group
P O Box 3707 MS4x-57
Seattle, WA 98023
(206)393-1973 Fax (206)393-5848
earl.e.wilhelm@boeing.com

Mr. D. Michael Williams
Director of Marketing
Litton Life Support
2734 Hickory Grove Road
Davenport, IA 52804-4508
(319)383-6361 Fax (319)383-6102

Mr. Dennis M. Williams
Sr. Project Engineer
McDonnell Douglas Corp.
Dept. 345, MC/270-3645
PO Box 516
Saint Louis, MO 63166-0516
(314)233-7984

Mr. Richard A. Williams
West Coast Marketing Manager
Talley Defense Systems
33582 Circula Corona
Dana Point, CA 35801
(714)661-7969 Fax (714)661-0338
raw@beach.net

Mr. Joel E. Williamsen
NASA
ED 52
Structural Development Branch
MSFC, AL 35812
(205)544-7007 Fax (205)882-0651

Mr. Robert T. Wirt
Intelligence Officer
Joint Strike Fighter (JSF)
Program Office
Suite 307
1745 Jefferson Davis Hwy
Arlington, VA 22202
(703)602-7390 Fax (703)602-0646
wirtr@ntrprs.jast.mil

Ms. Lisa H. Woods
Dir., Vulnerability & Testing
Booz, Allen & Hamilton Inc
Suite 131
4141 Colonel Glenn Highway
Dayton, OH 45431-1662
(937)431-2700 Fax (937)431-2721
woods-lisa@bah.com

Dr. C. Charles Yang
Assistant Professor
Wichita State University
Mechanical Engineering Dept.
Box 133
Wichita, KS 67260-0133
(316)978-6312 Fax (316)978-3236
yang@mc.twsu.edu

Ms. Kathleen M. Yerdon
Engineering Technologist, Sr.
Lockheed Martin Aeronautical S
86 South Cobb Drive
Dept. 73-D4, Zone 0685
Marietta, GA 30063-0685
(404)494-2869
Kathleen.m.yerdon@imco. com

Mr. James C. Young
Electronics Engineer
Naval Air Warfare Center
Code 4.1.8
Survivability Division
Patuxent River, MD 20670
(301)342-0157 Fax (301)342-8355
youngjc%amc@mr.nawcd.navy.mil

Mr. Harold H. Zucconi
Deputy Program Manager
ORION Int'l Tech., Inc.
Bldg 1407
Martin Luther King Jr. Ave.
White Sands, NM 88002
(505)678-7282 Fax (505)678-7293
zuccon@otd.osd.mil

(205)544-7007
(205)882-0651